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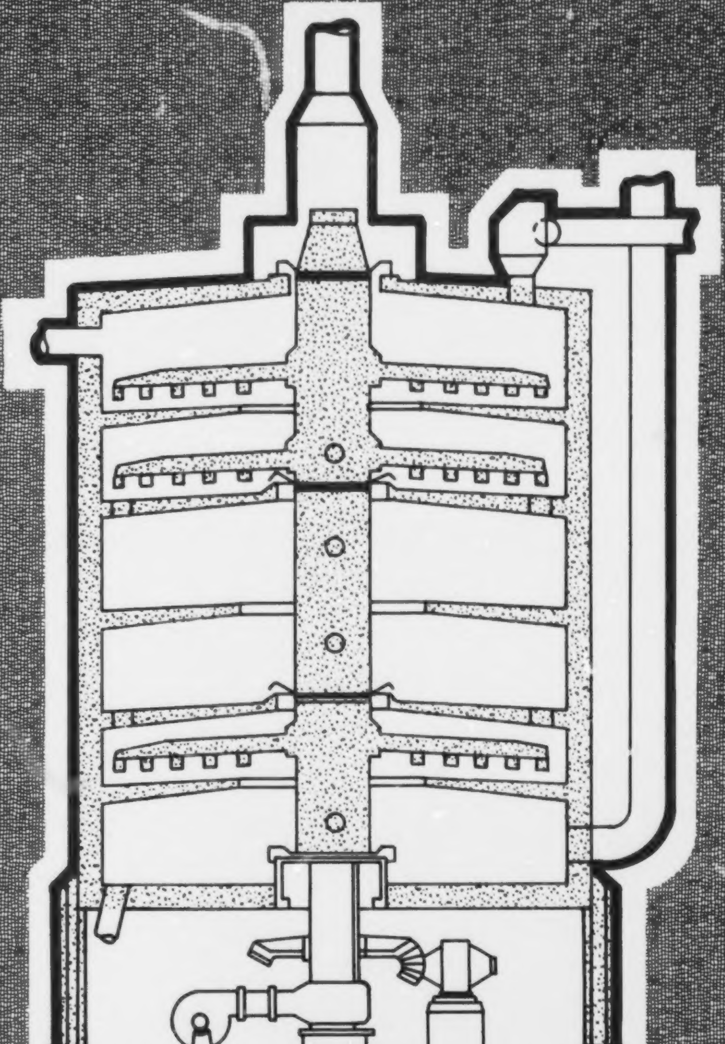

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This publication describes and evaluates the various municipal sludge combustion systems. It also emphasizes the necessity for considering and evaluating the costs involved in the total sludge management train, including dewatering, combustion, air pollution control, and ash disposal processes. It is intended to supplement but not replace EPA technology transfer publications on sludge treatment and disposal, dewatering municipal wastewater sludges, municipal sludge landfills, and land application of municipal sludge. It also answers questions that have been raised about incineration as a means of processing sludge solids for ultimate disposal and presents factual answers supported by case histories.

The primary objectives of this document are (1) to assess the current status of municipal sludge combustion technology as to performance of in-place systems, environmental concerns, and regulatory agency viewpoints; (2) to determine what needs to be done to make municipal sludge combustion more economical, including upgrading the performance of present and future systems; and (3) to discuss technology in the R&D stage.

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CENTER FOR ENVIRONMENTAL RESEARCH INFORMATION
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September 1985

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INTRODUCTION

This publication contains material prepared in association with the U.S. Environmental Protection Agency's International Conference on Thermal Conversion of Municipal Sludge. The conference was held in Hartford, Connecticut, March 21-24, 1983.

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The primary objectives of this document are (1) to assess the current status of municipal sludge combustion technology as to performance of in-place systems, environmental concerns, and regulatory agency viewpoints; (2) to determine what needs to be done to make municipal sludge combustion more economical, including upgrading the performance of present and future systems; and (3) to discuss technology in the R&D stage.

Many different, plausible schemes exist for treating municipal wastewater treatment plant sludge, but no single method is appropriate for all municipalities. Sludge properties, project size, and location are the primary considerations that enter into the identification of prudent approaches to sludge management. Common to all is the need to concentrate the collected solids and then to process them to minimize any adverse impact on the environment in ultimate disposal. Sludge concentration can be characterized in two steps: (1) the solids are taken out of the wastewater so that the plant's discharge permit can be met, and (2) a portion of the remaining water is removed from the solids so that processing for ultimate disposal can be achieved economically. This latter step becomes very important economically if a combustion process is chosen.

Sludge management is a difficult environmental control problem. The complexity of sludge processing decisionmaking is caused by factors such as the diversity of sludge characteristics, the wide range of processes available for use in sludge management, the interrelations between those processes, the interactions between the solids handling and wastewater treatment processes, the potential environmental and public health effects of sludge solids, the frequently high capital and operating costs involved, and the limitations imposed by concerns of the public.

However, given the quantities of wastewater sludge generated annually, an effort to reduce costs causes us to examine whether the energy potential of this sludge could be exploited by utilizing it in thermal processes. It is estimated that approximately 19 kg organic dry solids of wastewater sludge (0.080 kg × *365* × 0.65) are generated annually per inhabitant. If one considers that 1 kg of organic dry substance may have a calorific value of about 25,000 kJ (about 7 kWh), the energy value can be calculated to be about 19×7 = 133 kWh per inhabitant per year. Excessive auxiliary fuel is necessary if dewatering is not performed effectively. This is a consequence of the high energy requirements for water evaporation. As experience indicates, the successful utilization of wastewater sludge energy often means solving the problem of sludge dewatering. It takes far less energy to mechanically dewater sludge before incineration than it does to evaporate the same amount of water during incineration.

Most techniques or systems for processing solids involve a combination of several processes selected from a large pool of potential processes. Many alternative means exist to carry out each individual process. Thus, even designs involving only thermal processes can involve many different configurations.

Public sentiment is a major factor influencing sludge processing and ultimate disposal decisions. While considerable attention has been focused on ocean disposal and application to agricultural lands, sludge management designs involving thermal processing are not exempt from public concern, especially in the vicinity of a planned site.

In general, the public views sludge as a valuable resource. A recent example of this resource concept is Bio-brick One, a picnic shelter at the Brighton Dam Park in Montgomery County, MD, which is constructed of bricks made with up to 50 percent sludge content. These bricks have all the strength and utility of common construction bricks, and the sludge brick walls do not look or smell any different from other brick structures. Another consideration is fuel value; sludge solids contain oils, paper fibers, and other organics that can be burned directly or converted into a fuel oil that has the same heating value and characteristics as No. 2 fuel oil. The future looks promising for the use of sludge solids to produce energy for combustion, as heat is currently being recovered from the combustion processes at several wastewater plants.

CHAPTER I. SLUDGE INCINERATION FACILITIES

INTRODUCTION

High temperature processes have been used for combustion of municipal wastewater solids since the early 1900s. Popularity of these processes has fluctuated greatly since their adaptation from the industrial combustion field. In the past, combustion of wastewater solids was both practical and inexpensive. Solids were easily dewatered and the fuel required for combustion was cheap and plentiful. In addition, air emission standards were virtually nonexistent.

In today's environment, wastewater solids are more complex and include sludges from secondary and advanced waste treatment (AWT) processes. These sludges are more difficult to dewater and thereby increase fuel requirements for combustion. Due to environmental concerns with air quality and high costs, the use of high temperature processes for combustion of municipal solids is being scrutinized.

However, recent developments in more efficient solids dewatering processes and advances in combustion technology have renewed an interest in the use of high temperature processes for specific applications. High temperature processes should be considered where available land is scarce, stringent requirements for land disposal exist, destruction of toxic materials is required, or the potential exists for recovery of energy, either with wastewater solids alone or combined with municipal refuse.

High temperature processes have several potential advantages over other methods:

- Maximum volume reduction. Reduces volume and weight of wet sludge cake by approximately 95 percent, thereby reducing disposal requirements.
- Detoxification. Destroys or reduces toxics that may otherwise create adverse environmental impacts.
- Energy recovery. Potentially recovers energy through the combustion of waste products, thereby reducing the overall expenditure of energy.

This publication describes both proven high temperature processes and those having high probability of success, as indicated by current research. Multiple-hearth and fluidized-bed furnaces, the most commonly used sludge combustion equipment in the United States, Europe, Japan, and Great Britain, as well as newer furnace types, are discussed. New thermal processes for wastewater solids reduction are also described. These processes include starved-air combustion and cocombustion of sludges and other residues.

STRUCTURE AND FUNCTION OF MAJOR FURNACE TYPES

There are several types of combustors, or furnaces, commonly used today. They include the multiple-hearth furnace (MHF), fluidized-bed furnace (FBF), and electric (infrared) furnace (EF).

Multiple-Hearth Furnace

The MHF is the most widely used sludge incinerator. Earlier installations were at Dearborn, Michigan, in 1934; Minneapolis-St. Paul, Minnesota, 1938; and Cleveland, Ohio, 1941. As of 1977, approximately 196 units had been installed for municipal wastewater sludge combustion. The MHF is durable, relatively simple to operate unless sludgecake is extraordinarily dry, and can handle fluctuations in feed quality and loading rates. The MHF is best suited to continuous operation. Startup fuel requirements and the extended time needed to bring the hearths and internal equipment up to temperature from a completely cold condition normally make intermittent operations less advisable. Generally the temperature is maintained at "hot standby," usually 427°C (800°F) during loading stoppages of up to a few days.

The MHF is a vertically oriented, cylindrically shaped, refractory-lined steel shell containing a series of horizontal refractory brick hearths, one above the other. MHFs are available with diameters ranging from 1.4 to 8.8 m (4.5 to 29 feet) and can have from 4 to 14 hearths. For sludge combustion, a maximum of eight hearths is desirable.

A cross section of a typical MHF is shown in Figure I-1. A central shaft extends from the bottom of the furnace to the top and supports rabble arms above each hearth. There are either two or four rabble arms per hearth. Each arm contains several rabble teeth, or plows, which rake the sludge across the hearth in a spiral pattern. In the design shown, sludge is fed at the periphery of the top hearth and is rabbled toward the center, where it drops to the hearth below. On the second hearth, the sludge is rabbled outward to holes at the periphery of the hearth. Here the sludge drops to the next hearth. The alternating drop hole locations on each hearth and the countercurrent flow of rising exhaust gases and descending sludge provide contact between the hot combustion gases and the sludge feed. Good contact ensures effective drying and complete combustion.

Figure I-2 shows an interior cutaway view of the MHF. The central shaft of the furnace is a hollow iron column case in sections; shaft speeds are usually adjustable from about 0.3 to 3 revolutions per minute (RPM). The hollow rabble arms are inserted into machined arm sockets in the shaft. The shaft and rabble arms are air-cooled and normally insulated. A cold air tube is in the center of the shaft. Air lances extend from the cold air tube out to the ends of each rabble arm. Ambient air is forced through the cold air tube and lances by means of a blower. The cold air exits from the tips of the lances, flowing inward through the space between the lances and the rabble arm shell to the annular space in the central shaft. This flow of air cools the arms and the teeth by conduction. The heated air is either discharged to the atmosphere via the exhaust gas stack or returned to the bottom hearth of the furnace, or both if only part of this heated air is needed for sludge combustion. It may also be used for building heat; its temperature is typically 197°-232°C (350°-450°F).

The MHF can be divided into four zones, as shown in Figure I-3. The first zone, which consists of the upper hearths, is the drying zone. Most of the water is evaporated in the drying zone. The second zone, generally consisting of the central hearths, is the combustion zone. In this zone, the majority of combustibles are burned, and temperatures reach 760°-927°C (1,400°-1,700°F). The third zone is the fixed carbon burning zone, where the remaining carbon is oxidized to carbon dioxide. The fourth zone includes the lowest hearths and is the cooling zone. In this zone, ash is cooled by the incoming combustion air. The sequence of these zones is always the same, but the number of hearths in each zone is dependent on the quality of the feed, the design of the furnace, and the operational conditions. The zone transition often occurs partway across the hearth.

When the heating value of the sludge is insufficient to sustain autogenous combustion, the additional heat required is supplied by firing supplemental fuel in burners located at various points in the furnace wall. Burners may operate either continuously or intermittently and on any selected hearths.

Fluidized-Bed Furnace

The FBF is a vertically oriented, cylindrically shaped, refractory-lined steel shell that contains a sand bed and fluidizing air diffusers called tuyeres. Experience and hardware developed by FBF

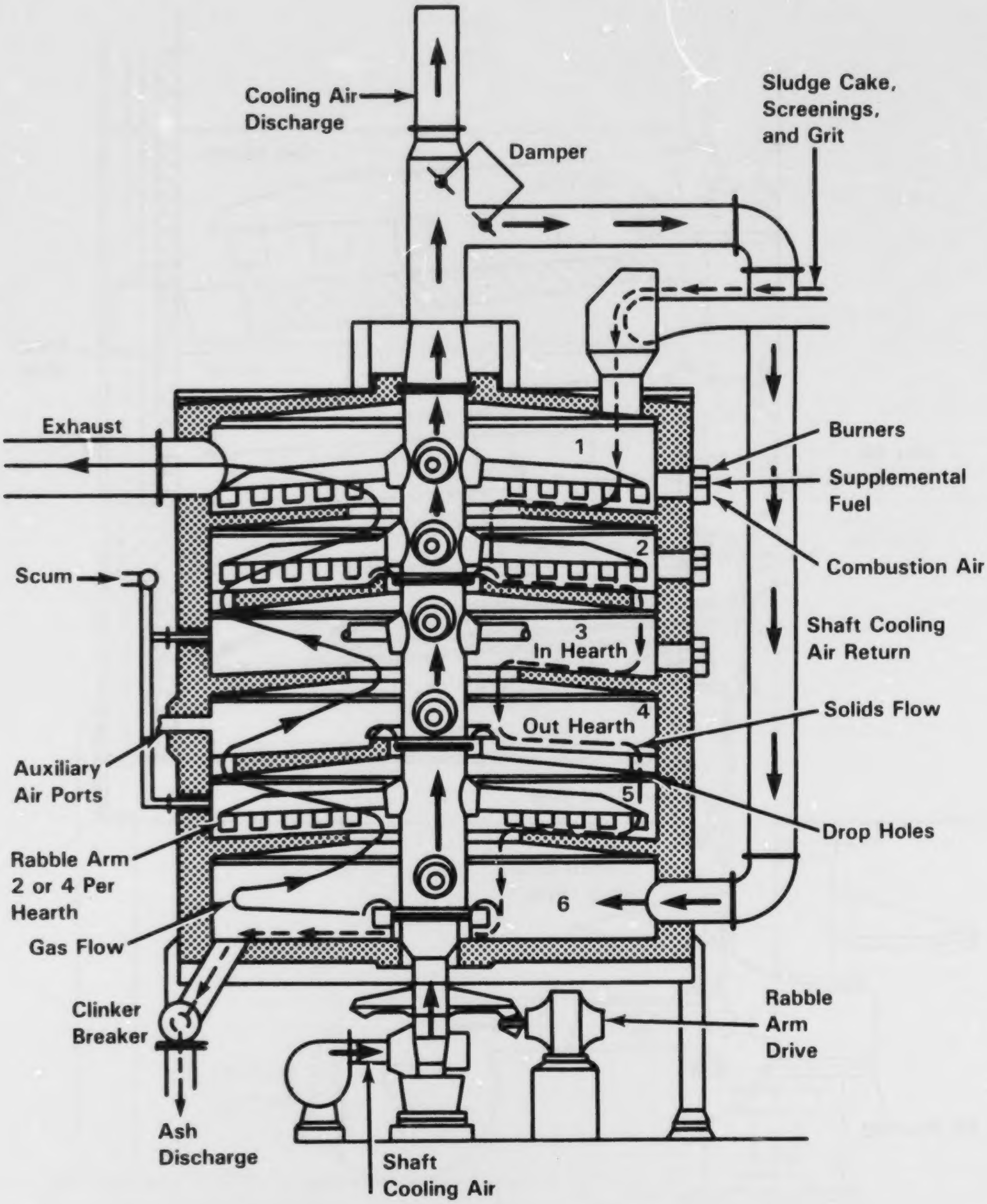
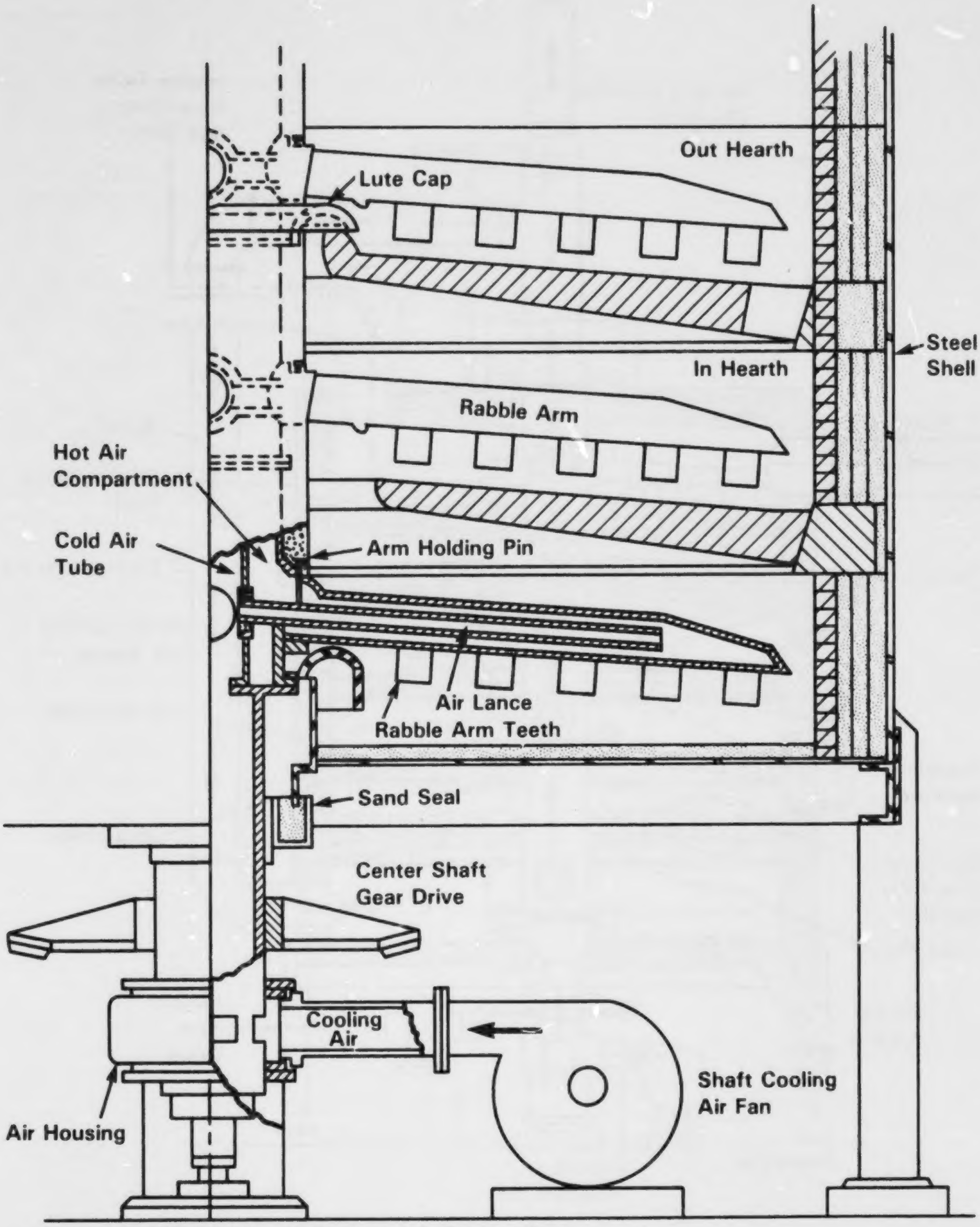

Cooling Air Discharge
Sludge Cake, Screenings, and Grit
Damper
Exhaust
Burners
Supplemental Fuel
Combustion Air
1
2
3
In Hearth
4
Out Hearth
5
6
Scum
Shaft Cooling Air Return
Solids Flow
Auxiliary Air Ports
Drop Holes
Rabble Arm 2 or 4 Per Hearth
Gas Flow
Clinker Breaker
Rabble Arm Drive
Ash Discharge
Shaft Cooling Air

Figure I-1. Cross section of a multiple-hearth furnace.


Out Hearth
Lute Cap
In Hearth
Steel Shell
Rabble Arm
Hot Air Compartment
Cold Air Tube
Arm Holding Pin
Air Lance
Rabble Arm Teeth
Sand Seal
Center Shaft Gear Drive
Cooling Air
Shaft Cooling Air Fan
Air Housing

Courtesy BSP Division of Environtech Corporation

Figure I-2. Interior cutaway view of a multiple-hearth furnace.

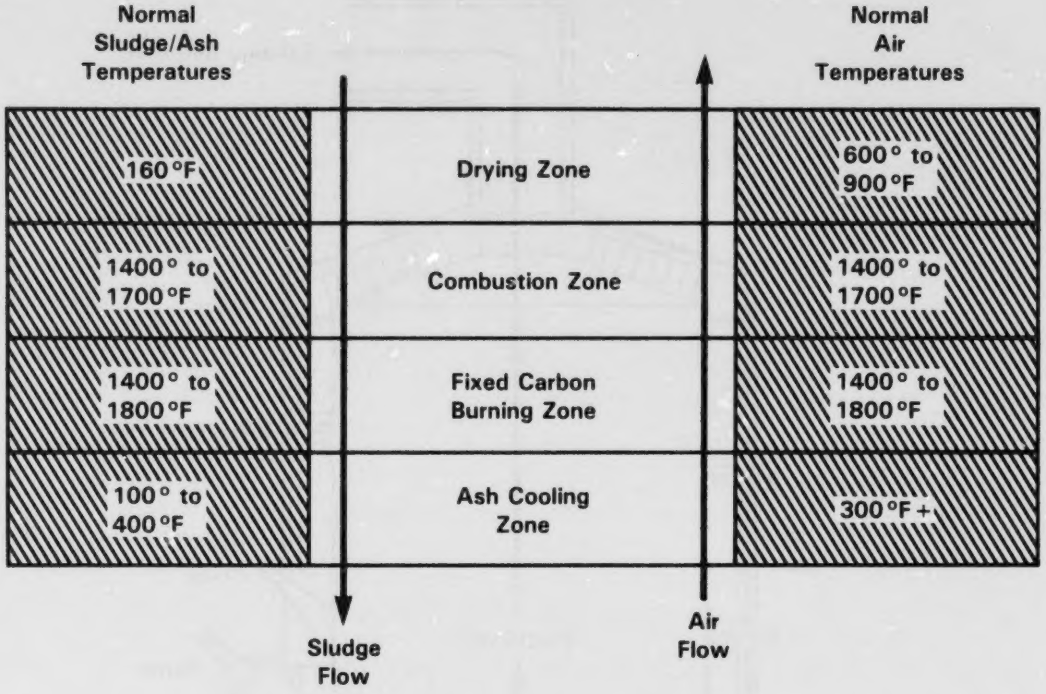

Normal
Sludge/Ash
Temperatures
Normal
Air
Temperatures
160 °F
Drying Zone
600° to
900 °F
1400° to
1700 °F
Combustion Zone
1400° to
1700 °F
1400° to
1800 °F
Fixed Carbon
Burning Zone
1400° to
1800 °F
100° to
400 °F
Ash Cooling
Zone
300 °F +
Sludge
Flow
Air
Flow

Figure I-3. Process zones in a multiple-hearth furnace.

manufacturers in the metallurgical and chemical industries have been applied in the combustion of municipal sludges. The FBF is normally available in sizes from 2.7 to 7.6 m (9 to 25 feet) in diameter. To date, units for wastewater sludge combustion operate with capacities of 2×10^6 to 74×10^6/kJ/hr (2×10^6 - 70×10^6 Btu/hr). Capacities of up to 211×10^6 kJ/hr (200×10^6 Btu/hr) per unit can be supplied with existing reactor and auxiliary hardware design. A cross section of the FBF is shown in Figure I-4. The sand bed is approximately 0.8 m (2.5 feet) thick and sits on a refractory-lined grid. This grid contains tuyeres through which air is injected into the furnace at a pressure of 21-34kN/m^2 gauge (3-5 psig) to fluidize the bed. The bed expands to approximately 200 percent of its at-rest volume. The temperature of the bed is controlled between 760° and 816°C (1,400° and 1,500°F) by auxiliary burners located either above or below the sand bed. In some installations, a water spray or heat-removal system in the bed controls the furnace temperature.

The reactor (Figure I-5) is a single chamber unit in which both drying and combustion occur in either the dense or dilute phases in the sand bed. All of the combustion gases and ash rise from the combustion zone after residence times of several seconds at 760° to 816°C (1,400° to 1,500°F). Ash is carried out the top of the furnace and is removed by air pollution control devices, usually Venturi scrubbers. Sand carried out with the ash must be replaced. Sand losses are typically 5 percent of the bed volume for every 300 hours of operation. Feed to the furnace is introduced either above or directly into the bed.

Airflow in the furnace is determined by several factors. Fluidizing and combustion air must be sufficient to expand the bed to a proper density yet low enough to prevent the sludge from rising to

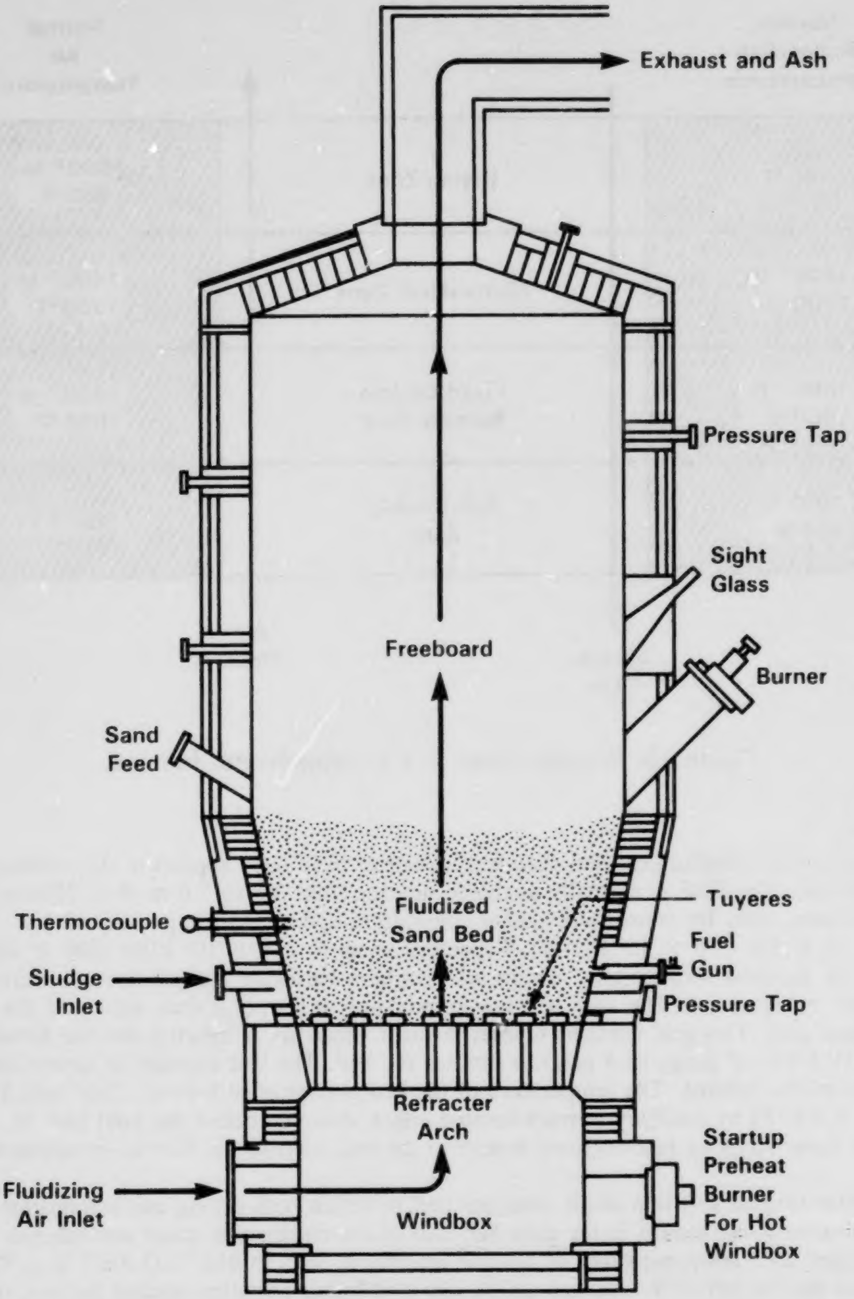

Exhaust and Ash
Pressure Tap
Sight Glass
Freeboard
Burner
Sand Feed
Tuyeres
Fluidized Sand Bed
Thermocouple
Fuel Gun
Sludge Inlet
Pressure Tap
Refracter Arch
Startup Preheat Burner For Hot Windbox
Fluidizing Air Inlet
Windbox

Figure I-4. Cross section of a fluidized-bed furnace.

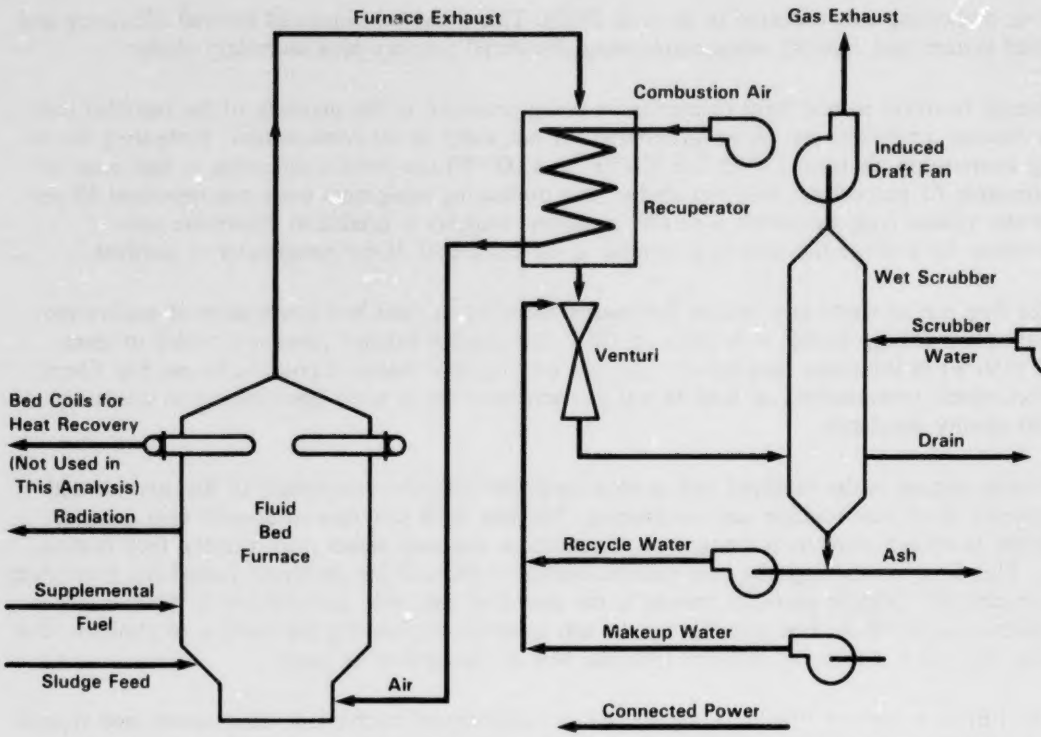

Furnace Exhaust
Gas Exhaust
Combustion Air
Induced
Draft Fan
Recuperator
Wet Scrubber
Scrubber
Water
Venturi
Bed Coils for
Heat Recovery
(Not Used in
This Analysis)
Drain
Radiation
Fluid
Bed
Furnace
Recycle Water
Ash
Supplemental
Fuel
Makeup Water
Sludge Feed
Air
Connected Power

Figure I-5. Flowsheet for sludge incineration in a fluidized-bed furnace.

and floating on top of the bed. Too much air blows sand and products of incomplete combustion into the off-gases. This depletes stored heat energy and increases fuel consumption unnecessarily. Minimum oxygen requirements must be met to assure complete oxidation of all combustible solids in the sludge cake. Temperatures must be sufficiently high to assure complete deodorizing but low enough to protect the refractory, heat exchanger, and flue gas ducting and to prevent slag formation.

The quantity of excess air is maintained in the range of 20 to 45 percent to minimize fuel cost. The FBF operates at much lower excess air rates than typically required in MHF operations. This accounts for the greater heat efficiency of the fluidized-bed system at similar exit temperatures.

There are two basic process configurations for the FBF. In one design, the fluidizing air passes through a heat exchanger, or recuperator, prior to injection into the combustion chamber. This arrangement is known as a hot windbox (HWB) design. In the other design, the fluidizing air is injected directly into the furnace. This arrangement is known as a cold windbox (CWB) design. The first arrangement increases the thermal efficiency of the process by using the exhaust gases to preheat the incoming combustion air but adds substantial capital costs.

The world's first fluidized-bed unit for municipal wastewater sludge treatment was built at Lynnwood, WA. This small CWB unit with no internal heat recovery went into operation in 1965 and continues to operate today. Design capacity is 95 kg/hr (210 lb/hr) of centrifuge-dewatered primary sludge solids, requiring little, if any, auxiliary fuel for normal operation. The development of the

HWB air preheating unit occurred in the mid-1960s. This provided improved thermal efficiency and increased system unit capacity when combusting dewatered primary plus secondary sludge.

Energy recovery in one form or another is being practiced in the majority of the installed units by combustion air preheating, steam generation, or hot water or oil economizers. Preheating the incoming combustion air from 21° to 538°C (70° to 1,000°F) can yield a reduction in fuel costs of approximately 61 percent per unit wet sludge. Air preheating equipment costs can represent 15 percent of the system cost; therefore, a careful economic analysis is needed to determine cost-effectiveness for a given situation to determine if the extra cost of the recuperator is justified.

The first use of waste heat boilers for energy recovery in fluid bed combustion of wastewater treatment plant sewage sludge took place in 1968. The reactor exhaust gases are cooled to about 180°C (350°F) in the waste heat boiler. This gas cooling then makes it possible to use bag filters and electrostatic precipitators, as well as wet gas scrubbers for exhaust gas cleaning as necessary to meet air quality standards.

Violent mixing in the fluidized bed assures rapid and uniform distribution of fuel and air and consequently good heat transfer and combustion. The bed itself provides substantial heat capacity. This helps to reduce short-term temperature fluctuations that may result from varying feed heating values. This heat storage capacity also enables quicker startup, if the shutdown period has been short (e.g., overnight). Organic particles remain in the sand bed until they are reduced to mineral ash. The violent motion of the bed comminutes the ash material, minimizing the buildup of clinkers. The resulting fine ash is constantly stripped from the bed by the upflowing gases.

The FBF is relatively simple to operate, has a minimum of mechanical components, and typically has a slightly lower capital cost than the MHF. Normal operation of the FBF produces exhaust temperature in excess of 760°C (1,400°F). Because the exhaust gases are exposed to this temperature for several seconds, odors and carbonyl and unburned hydrocarbon emissions are minimal, and strict hydrocarbon emission regulations are met without the use of an afterburner. However, it is important that operating conditions be optimum to assure this emission level at all times.

Electric Furnace

The EF is a horizontally oriented, rectangular steel shell containing a moving horizontal woven-wire belt. EFs are available in a range of sizes from 1.2 m (4 feet) wide by 6.1 m (20 feet) long to 2.9 m (9.5 feet) wide by 29.3 m (96 feet) long. Larger sizes are currently being developed. A typical cross section is shown in Figure I-6.

Sludge is fed into the EF through a feed hopper that discharges onto the woven-wire belt. Shortly after the sludge is deposited on the belt, it is leveled by means of an internal roller to a layer approximately 2.5 cm (1 inch) thick across the width of the belt. A rabbling device is provided to break up the surface of the sludge layer to promote better combustion. This layer of sludge moves under the infrared heating elements, which provide supplemental energy for the drying process, if required. Ash is discharged from the end of the belt to the ash handling system. Combustion airflow is countercurrent to the sludge flow, with most of the combustion air being introduced into the ash discharge end of the unit. Excess air rates for EF vary from 29 to 70 percent. The EF is divided into a feed zone, a drying and combustion zone, and an ash discharge zone. The feed and discharge zones are each 2.4 m (8 feet) long. The length of the drying and combustion zone varies with the design.

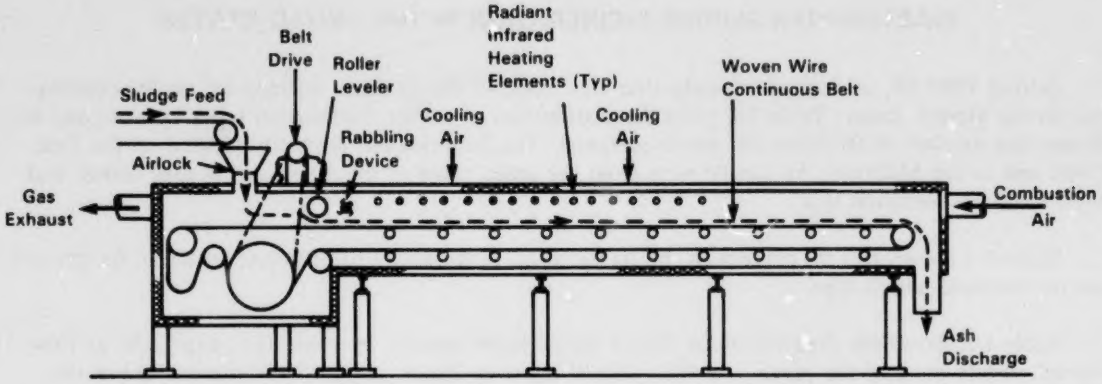


Figure I-6. Cross section of an electric (infrared) furnace.

The effective belt loading rate of a large EF is slightly greater than the hearth loading rate of a MHF. The supplemental energy requirements of the EF are lower than the requirements of the MHF, FBF, or the cyclonic furnace. Because electricity is used to provide the supplemental energy, no fuel is burned; consequently, excess air for this purpose is not required. However, electricity is generally a more expensive energy source than the fossil fuel used by the other unit types. Depending upon the energy cost differential, the advantage of low excess air may be reduced. When autogenous (self-sustaining) sludge is available, the only difference between the EF and other processes with low excess air rates would be the motive power.

Low capital cost combined with modular construction makes the EF attractive, especially for small treatment systems. Because of the use of ceramic-fiber blanket insulation instead of solid refractories, the electric furnace may be shut down and heated up without the refractory problems that can occur in the other furnaces. This makes the EF suitable for intermittent operation. However, each restart requires supplemental energy (electricity), since there is no heat sink similar to the sand bed in the FBF. The largest EF units currently installed have a rated capacity of 1,320 kg (2,920 lbs) of dry solids per hour and are located at the Snapfinger Creek Wastewater Treatment Plant, Decatur, Georgia.

The EF appears to be a feasible alternative for both small and large systems due to its inherent simplicity and low cost. However, the EF requires considerably more floor space than furnaces that are vertically oriented. Another concern is the replacement of various components such as the woven-wire belt (3- to 5-year life) and the infrared heaters (3-year life). These items represent more than 50 percent of the capital cost. Replacement costs must be considered in any overall evaluation.

Using electric utility power, whether for heating or motive power, may create a large electric demand charge in some areas. This may be the case whether the energy is used or not. Also, time-of-day charges could be significant.

Units of this type in industrial service have shown very severe corrosion in the shell metal, evidently caused by vapors condensing in the cooler sections. This has occurred in EF units processing carbon for activation. Similar attack might be expected in some units handling municipal sludge cake where a large percentage of industrial wastewater is treated.

WASTEWATER SLUDGE INCINERATION IN THE UNITED STATES

During 1982-84, an indepth investigation was made of the facilities utilized for sludge combustion in the United States. Table I-1 gives the distribution of sludge combustion types by state and indicates the number of facilities that are operational. The facilities are primarily located on the East Coast and in the Midwest. As can be seen from the table, most of the plants are in nine states, and MHFs are the dominant type.

Table I-2 shows that 58 percent of the incineration facilities are operational; of these, 61 percent are the multiple-hearth type.

Table I-3 shows the distribution of sludge incineration systems by plant size, expressed as flow treated. While most of the plants are 438 L/S (10 mgd) or larger, a significant number are in the 43.8 to 219 L/S (1 to 5 mgd) range but the ratio of operating plants to total goes up as the plant size increases. It is likely that smaller plants are in more rural areas where land disposal is practical, and that in some of these smaller plants incineration is not a least-cost method.

Those facilities noted to be nonoperational were either no longer in service, still in construction or startup, being retrofitted, or used seasonally. In some situations the exact status is indicated in the tables. Reasons given for nonuse included finding of lower cost options, air emission problems, or major design and mechanical/operational problems. Lower costs were reported for sludge treatment/disposal by agricultural utilization, landfilling, composting, lagooning, and ocean discharge.

Tables I-4 through I-8 show the locations, as of early 1984, of the 206 existing sludge incinerators handling municipal sludge solids from primary, secondary, and advanced treatment. The wastewater flows shown have been rounded for clarity and may be either design or actual averages, depending on the source of information. They are shown only to establish magnitude of plant size and, presumably, the sizes of the solids processing system.

WASTEWATER SLUDGE INCINERATION IN EUROPEAN COUNTRIES

Table I-9 shows the enormous amounts of wastewater treatment sludge that are produced per year. The table only provides a rough indication since the figures given refer to different years; are sometimes estimated or calculated on the basis of served inhabitants; sometimes comprise municipal wastewater sludge only; and sometimes include industrial wastewater sludges and dredged materials, as well as other wastes. Figures for the United States are included for comparative purposes.

Column 3 in Table I-9 gives data for the amount of sludges incinerated. The percentage varies between 1 and 15 percent for the European countries, indicating that incineration does not currently play a major role in wastewater sludge treatment. An unusually high percentage (25 percent) has been reported for the United States. The reason for this may be that auxiliary fuel in Europe has always been much more expensive than in the United States and, for economic reasons, sludge incineration only took place in high-capacity wastewater treatment plants or areas that had no other available utilization or disposal options.

WASTEWATER SLUDGE INCINERATION IN THE FEDERAL REPUBLIC OF GERMANY

Most units are either multiple-hearth or fluidized-bed configurations (see Chapter II for a detailed discussion of the design of these types of systems). The FBF appears to be more prevalent. At present, rotary kilns are rarely used in municipal sludge processing.

Table I-1. *Distribution of sludge combustion facilities by state and type.*

State	Multiple-Hearth		Fluidized-Bed		Electric (infrared)		Rotary Kiln		Cocombustion	
	Total	Operat'g	Total	Operat'g	Total	Operat'g	Total	Operat'g	Total	Operat'g
Alaska	2	1			2	1				
Arkansas	1	0	2	1						
California	9	5	5	2			1	1		
Colorado	1	0								
Connecticut	13	8	4	1					1	1
Florida	2	1								
Georgia	4	4			2	2			1	1
Hawaii	2	1								
Illinois	4	1								
Indiana	2	1	1	1						
Iowa	2	2	1	1						
Kansas	2	2	2	2						
Kentucky	2	0			1	1				
Louisiana	3	3	1	1						
Maryland	5	2	1	1						
Massachusetts	9	4	2	0			1	0		
Michigan	20	10	2	1	1	0				
Minnesota	2	2								
Missouri	2	1	3	0						
Nebraska			1	1						
Nevada	2	0	1	0						
New Hampshire	3	3								

Table I-1. *Distribution of sludge combustion facilities by state and type. (Continued)*

State	Multiple-Hearth		Fluidized-Bed		Electric (infrared)		Rotary Kiln		Cocombustion	
	Total	Operat'g	Total	Operat'g	Total	Operat'g	Total	Operat'g	Total	Operat'g
New Jersey	11	10	6	5						
New York	30	20	10	3	1	1			1	0
North Carolina	2	0	2	1						
Ohio	12	10	2	0						
Oklahoma	2	0								
Oregon	1	1								
Pennsylvania	17	9	5	2						
Rhode Island	3	0								
South Carolina	2	2								
Tennessee	4	3	1	1						
Texas	1	0			4	2				
Virginia	10	9	1	0						
Washington	1	1	1	1	1	1				
West Virginia	2	1								
Wisconsin	5	2								
Puerto Rico	1	1								
TOTALS	196	120	54	25	12	8	2	1	4	2

Table I-2. *Operational status of various types of installations.*

Type of Combustor at Facility	Number of Facilities	Number That Are Operating (%)
Multiple-hearth furnace	196	120 (61)
Fluidized-bed furnace	54	25 (46)
Electric infrared furnace	12	8 (67)
Rotary kiln	2	1 (50)
Cocombustion with refuse	4	2 (67)
TOTALS	268	156 (58)

Table I-3. *Distribution of sludge combustion systems by plant size.*

	Flow (mgd)a					
	0-1	1.1-5	5.1-10	10.1-25	25.1-50	50.1+[b]
Systems in operation	5	28	18	60	23	17
Systems not operating	9	22	18	12	5	5
TOTALS	14	50	36	72	28	22
Percentage in operation	36	56	50	83	82	77

[a] mgd = 43.8 L/S

[b] In the category of plants larger than 50 mgd, virtually all of these have multiple units, so a count based on units installed would possibly show the rising trend continuing.

Table I-4. *Multiple-hearth sludge incineration facilities in the United States. (Operational status as of April 1984)*

Major City or Area	Owning Authority	Plant Name	Flow (mgd = 43.8 L/S)	Status*	Waste Heat** Recovery
Anchorage, AK	Anchorage W&WW Utilities	Point Woronzof WWTP	24	O	Y
Fairbanks	City of Fairbanks	Fairbanks STP	4	N	—
Little Rock, AR	Little Rock WW Auth	Ut Adams Field TP	25	N	—
Monterey, CA	Monterey Reg CSD	Monterey WWTF	9	N	—
Palo Alto	City of Palo Alto	Palo Alto WWTF	26	O	N
Richmond	Richmond Muni Services	Richmond WWTF	7	N	—
Sacramento	Sacramento Reg Co SD	Sacramento Reg WWTP	136	N	—
San Leandro-Castro Val	Oro Loma SD	Oro Loma WWTF	9	N	—
San Mateo	City of San Mateo	San Mateo WQCP	12	O	Y
South Lake Tahoe	South Tahoe PUD	South Tahoe WWTF	6	O	Y
Walnut Creek-Concord	Central Contra Costa SD	CCCSD WWTF	35	R	Y
Yosemite Natl Park	National Park Service	Yosemite Park WWTF	2	I	—
Vail, CO	Vail W&SD	Vail STP	1	I	—
Bridgeport, CT	City of Bridgeport	Bridgeport Eastside	10	N	—
Same	Same	Bridgeport Westside	20	N	—
Cromwell	Mattabassat Dist Comm	MDC WPCG	19	O	N
Enfield	Town of Enfield	Enfield WWTP	—	O	—
Glastonbury	Town of Glastonbury	Glastonbury WPCF	1	N	—
Hartford	Hartford Metro Dist Commission	Hartford WPCF	48	N	—
Middletown	Town of Middletown	Middletown WPCF	4	N	—
New Haven	City of New Haven	East Shore WPCF	9	O	N
Same	Same	Boulevard WPCF	12	O	N
New London	City of New London	New London WPCF	3	O	N
Rockville	Vernon Sewer Commission	Vernon WPCF	2	O	N
Waterbury	City of Waterbury	Waterbury WPCF	22	O	N
Willimantic	Willimantic Sewer Commission	Willimantic WPCF	3	O	N
Jacksonville, FL	City of Jacksonville	Buckman Street STP	30	N	N
Pensacola	City of Pensacola	Main Street Plant	8	O	N
Atlanta, GA	Fulton County	RM Clayton	84	O	N
Same	Same	Utoy Creek	28	O	N
Cobb County	Cobb County	Chatahoochee	17	O	N
Savannah	City of Savannah	President St WPCF	18	O	N

Table I-4. *Multiple-hearth sludge incineration facilities in the United States. (Operational status as of April 1984) (Continued)*

Major City or Area	Owning Authority	Plant Name	Flow (mgd = 43.8 L/S)	Status*	Waste Heat** Recovery
Honolulu, HI	City and County of Honolulu	Sand Island WWTF	62	O	Y
Southwest Oahu	Same	Honolulu WWTP	25	S	Y
Decatur, IL	Decatur San District	Decatur STP	25	O	N
Granite City	Granite City San Dist	Granite City STP	7	N	—
Rock Falls	City of Rock Falls	Rock Falls STP	2	N	—
Rockford	Rockford San District	Rockford SD STP	39	N	—
East Chicago, IN	City of E Chicago	East Chicago STP	15	I	—
Indianapolis,	City of Indianapolis	Belmont St (STP #1)	125	O	N
Cedar Rapids, IA	City of Cedar Rapids	Cedar Rapids WPCF	25	O	Y
Davenport	City of Davenport	Davenport WWRP	19	O	Y
Johnson City, KS	Johnson Co Unif SD	Mission Twp STP	35	O	N
Shawnee Mission	Same	Turkey Creek, MSD #1	6	O	N
Bromley, KY	Campbell-Kenton Counties SD	Bromley WWTP	24	N	Y
Louisville	Louisville-Jefferson County	Morris Forman WWTP	88	N	Y
Algiers, LA	New Orleans Sewer and Water Bd	West Bank STP	12	O	N
Lake Charles	City of Lake Charles	Plant C	3	O	N
Same	Same	Plant B	2	O	N
Annapolis, MD	Ann Arundel County DPW	Annapolis City STP	4	N	N
Same	Same	Cox Creek WWTP	8	N	—
Baltimore	City of Baltimore	Patapsco	45	O	N
Piscataway	Washington Suburban San Comm	Piscataway WWTP	14	N	N
Upper Marlboro	Same	Western Branch WWTP	30	O	Y

Table I-4. *Multiple-hearth sludge incineration facilities in the United States.*
(Operational status as of April 1984)
(Continued)

Major City or Area	Owning Authority	Plant Name	Flow (mgd = 43.8 L/S)	Status*	Waste Heat** Recovery
Attleboro, MA	City of Attleboro	Attleboro WWTW	4	O	Y
Chicopee	City of Attleboro	Chicopee WWTP	5	O	N
Fitchburg	City of Fitchburg	Fitchburg East WWTP	1	I	N
Hull	Town of Hull	Hull WWTP	.5	N	—
Lawrence	Greater Lawrence San Dist	Greater Lawrence SD WWTP	38	O	N
New Bedford	City of New Bedford	New Bedford WWTP			
Quincy	Metro Dist Comm (Boston)	Nut Island WWTP	128	I	—
Salem	Essex Sewerage Dist	South Essex WWPCF	23	N	—
Worcester	Upper Blackstone WPC Dist	Upper Blackstone Reg WWTP	32	O	N
Ann Arbor, MI	Washtenaw Co DPW	Ypsilanti Comm WWTP	10	O	Y
Ann Arbor	City of Ann Arbor	Ann Arbor WWTP	16	O	N
Bay City	City of Bay City	Bay City STP	12	O	N
Bay County	Bay County	Bay County SKTP	12	S	—
Detroit	Detroit Water Bd	Detroit STP	698	O	N
East Lansing	City of E Lansing	E Lansing WWTP	11	O	Y
Flint	City of Flint	Flint WPCF	42	N	—
Grand Haven	Grand Haven-Spr Lake SD	City of Grand Haven STP	5	N	—
Grand Rapids	City of Grand Rapids	Grand Rapids STP	50	O	Y
Grandville	Wyoming County	Wyoming Co WWTP	12	N	—
Genessee	Genessee County	Genessee Co STP	42	N	—
Kalamazoo	Kalamazoo Wastewater Sys	Kalamazoo WQTP	33	R	Y
Lansing	City of Lansing	Lansing WWTP	28	N	Y
Niles	Berrien Co DPW	Niles WWTP	4	I	Y
Owosso	City of Owosso	Owosso WWTP	3	O	N
Pontiac	City of Pontiac DPW	Pontiac STP	20	O	N
Saginaw	Saginaw Township	SW Dist Saginaw Twp STP	3	N	—
Trenton	City of Trenton	Trenton WWTP	6	O	N
Watervliet	Paw-Paw Lake SD	Paw-Paw Lake WWTP	1	N	—
Wayne County	Wayne County	Wyandotte STP	45	O	N
Mpls-St Paul, MN	Metro Waste Control Comm	Metropolitan WWTP	250	O	Y
South Suburban T/C Area	Same	Seneca WWTP	24	O	N
St. Louis, MO	Metropol San Dist	Bissell Point STP	140	O	N
Same	Same	Lemay STP	110	R	Y

Table I-4. *Multiple-hearth sludge incineration facilities in the United States.*
(Operational status as of April 19S4)
(Continued)

Major City or Area	Owning Authority	Plant Name	Flow (mgd = 43.8 L/S)	Status*	Waste Heat** Recovery
Carson City, NV	Carson City DPW	Carson City WWTP	3	N	—
Las Vegas Suburban	Clark Co San Dist	CCSD #1 WWTF	25	N	—
Lebanon, NH	City of Lebanon	Lebanon WWTF	1	O	N
Merrimack	Merrimack Bd of Selectmen	Merrimack WWTP	2	O	N
Manchester	City of Manchester	Manchester WWTP	26	O	—
Atlantic City, NJ	Atlantic Co San Auth	Atlantic Co STP	40	O	Y
Jersey City	Jersey City Sewerage Auth	East Side STP	35	N	—
Pequannock-Lincoln Park	Two Bridges SA	Pequannock-LP-Fairfield STP	3	O	—
Princeton	Stony Brook RSA	Stony Brook RSA STP #1	4	O	—
Somerville-Bridgewater	Somerset-Raritan SA	Somerset-Raritan STP	15	O	—
Union Beach	Bayshore Regional SA	Bayshore Regional STP	8	O	—
Wayne Township	Mountain View Sew Auth	Mountain View STP	24	O	—
Albany, NY	Albany Co Sew Dist	North WWTP	—	O	—
Same	Same	South WWTP	—	O	—
Amherst	Town of Amherst	Amherst WWTP	8	O	Y
Auburn	Auburn DPW	Auburn STP	9	N	—
Beacon	City of Beacon	Beacon WPCP	4	O	—
Briarcliff Manor	Briarcliff Manor DPW	River Rd & Scarborough TFs	.2	N	—
Buffalo	Buffalo Sew Auth	Birds Island STP	178	O	Y
Canajoharie	Village of Canajoharie	Canajoharie STP	.5	N	—
Cortland	City of Cortland	Cortland STP	6	N	—
Croton-on-Hudson	Vil of Croton-on-Hudson	SOH SS	1	N	—
Dunkirk	City of Dunkirk	Dunkirk STP	6	O	—
Greece	Monroe Co SA	NW Quadrant TP	11	O	—
Mamaroneck	Westchester Co DEF	Mamaroneck San Sew Dist	15	O	—
New Rochelle	Westchester Co DEF	New Rochelle SD STP	16	O	Y
New Windsor	City of New Windsor	New Windsor STP	5	N	—
N. Tonawanda	Town of N. Tonawanda	N. Tonawanda STP	8	O	—
Orangetown	Town of Orangetown DPW	Orangetown STP	7	O	—
Ossining	Westchester Co DEF	Ossining WWTP	10	O	—
Oswego	City of Oswego	Oswego East STP	3	O	—
Same	Same	Oswego West STP	4	O	—
Port Chester	Westchester Co DEF	Port Chester SD STP	7	O	—

Table I-4. *Multiple-hearth sludge incineration facilities in the United States. (Operational status as of April 1984) (Continued)*

Major City or Area	Owning Authority	Plant Name	Flow (mgd = 43.8 L/S)	Status*	Waste Heat** Recovery
Rochester, NY (Cont)	Brighton SD #2	Allens Creek TP	9	N	–
Same	Gates-Chili-Ogden SD	Gates-Chili-Ogden STP	11	O	–
Same	Rochester Pure Water Dist	Frank E. Van Lare WWTP	69	O	–
Schenectady	City of Schenectady	Schenectady STP	14	O	–
Southampton	Suffolk Co DEC	Disposal Dist #15	30	O	–
Syracuse	Syracuse Metro SA	Ley Creek STP	17	N	–
Tarrytown	Village of Tarrytown	Tarrytown STP	2	N	–
Tonawanda	Two-Mile Creek San Dist	Two-Mile Creek SD Plant	14	O	Y
Wheatfield	Niagara Co SD #1	Niagara Co SD #1 STP	14	S	–
Greensboro, NC	City of Greensboro	North Buffalo WTP	10	S	Y
Rocky Mountain	City of Rocky Mountain	Rocky Mountain WWTP	10	O	–
Akron, OH	City of Akron	Akron WWTP	79	O	–
Canton	City of Canton	Canton WWTP	33	O	–
Cincinnati	Metro Sew Dist, Cincinnati	Mill Creek WWTP	107	O	–
Same	Same	Little Miami WWTP	38	O	Y
Cleveland	NE Ohio Reg San Dist	Westerly WWTP	50	O	N
Same	Same	Southerly WWTP	110	O	Y
Columbus	City of Col. Div of Sew	Jackson Pike WWTP	92	O	–
Same	Same	Southerly WWTP	–	C	Y
Euclid	City of Euclid	Euclid WWTP	17	O	–
Newark	City of Newark	Newark STP	10	N	–
Youngstown	City of Youngstown	Youngstown WWTP	29	O	–
Lawton, OK	City of Lawton	Lawton STP	6	N	–
Muskogee	City of Muskogee	Muskogee STP	12	N	–
Tigard, OR	United Sewerage Agency	Durham Reg STP	8	O	–
Ambridge, PA	Ambridge Boro Mun Auth	Ambridge STP	1	O	–
Apollo-Leechburg	Kiski Valley WPC Auth	Kiski Valley WPCP	3	O	–
Bridgeport	Bridgeport Boro Auth	Bridgeport STP	.5	O	–
Chester	Delaware Co Reg WQC Auth	Delcora-Chester STP	36	O	–
Colmar	Hatfield Twp Muni Auth	Hatfield Twp STP	2	O	–

Table I-4. *Multiple-hearth sludge incineration facilities in the United States.* *(Operational status as of April 1984)* *(Continued)*

Major City or Area	Owning Authority	Plant Name	Flow (mgd = 43.8 L/S)	Status*	Waste Heat** Recovery
Downington, PA (cont)	Boro of Downington	Downington Reg WWTP	3	N	—
Duryea	Lwr Lackawanna Val Sew Auth	LLVSA WWTP	6	I	N
Erie	Erie Sewer Auth	Erie City STP	63	I	Y
Hershey	Derry Twp Mun Auth	Derry Twp WPCP	2	N	—
Lemoine Boro	—	Cumberland City STP	—	—	—
McKeesport	Boro of Morrisville	Morrisville WWTF	4	N	—
Norristown	Norristown-Plymouth JS Auth	E Norristown-Plymouth TP	5	O	—
Pittsburgh	Allegheny Co San Auth	Alcosan WWTP	200	C	Y
Sunbury	Sunbury Muni Auth	Sunbury Sew Treat System	2	N	—
Wilkes-Barre	Wyoming Valley San Auth	Wyoming Valley SA STP	25	O	—
Willow Grove	Upper Moreland-Hatboro SA	Upper Moreland-Hatboro TP	4	O	—
York	Hummelstown-Swatara Twp Auth	—	26	O	Y
Cranston, RI	City of Cranston DPW	Cranston WPCF	9	C	Y
Providence	City of Providence	Fields Point STP	60	N	—
Smithfield	Smithfield Sew Auth	Smithfield WWTF	1	N	—
Charleston, SC	City of Charleston	Plum Island TP	15	O	—
Columbia	City of Columbia	Metropolitan TP	22	O	—
Bristol, TN	Cities of Bristol (TN & VA)	Bristol WWTP #2	10	O	—
Maryville	Maryville Bd Util	Maryville Reg STP	3	O	—
Nashville	Nashville Met Govt	Nashville Cent WWTP	51	O	—
Irving, TX	Trinity Riv Auth	Central STP	100	N	Y
Arlington, VA	Arlington County	Arlington Co WPCP	23	S	Y
Fairfax	Fairfax County	Lower Potomac STP	23	O	—
Hopewell	City of Hopewell	Hopewell Reg WWTF	40	O	Y
Newport News	Hampton Roads SD	Boat Harbor WPCF	18	O	—
Norfolk	Same	Lamberts Point WPCF	28	O	—
Same	Same	Army Base WPCF	14	O	—
Virginia Beach	Same	Chesapeake-Elizabeth WPCF	25	O	Y
Williamsburg	Same	Williamsburg WPCF	6	O	—
Woodbridge-Occoquan	Prince William County	Potomac River STP	—	O	—

Table I-4. Multiple-hearth sludge incineration facilities in the United States.
(Operational status as of April 1984)
(Continued)

Major City or Area	Owning Authority	Plant Name	Flow (mgd = 43.8 L/S)	Status*	Waste Heat** Recovery
Vancouver, WA	City of Vancouver	Westside WWTP	18	O	N
Clarksburg, WV	Clarksburg San Bd	Clarksburg STP	5	O	—
Huntington	Huntington San Bd	Huntington STP	15	N	—
Brookfield, WI	City of Brookfield	Brookfield STP	10	O	—
Green Bay	Green Bay MSD	Green Bay WWTP	29	O	Y
Marinette	City of Marinette DPW	Marinette WWTP	4	N	—
Milwaukee	Milwaukee Sew Comm	South Shore WWTP	72	N	—
Oshkosh	City of Oshkosh	Oshkosh WTP	10	N	—
San Juan, PR	PR Aqueduct & SA	Puerto Nuevo WWTP	47	O	—

* O = System is in operation regularly and used on a year-round basis.
N = System is not used; a more economical alternative is preferred.
I = System is used intermittently (low loading) or seasonally.
S = System is in startup status and not handling routine loading.
R = System is being remodeled or upgraded and has operated previously.
C = System is under construction.
- = No data available at this time.

** WHR column indicates if a waste heat recovery device is included (Y) or not (N).
A dash (-) indicates no information was obtained and generally means no device.
Pre-heater recuperators for HWB fluidized-bed units that do not export heat are not classified as WHR devices.

Table I-5. *Fluidized-bed sludge incineration facilities in the U.S.*

Major City or Area	Owning Authority	Plant Name	Flow (mgd = 43.8 L/S)	Status*
Fort Smith, AR	—	—	—	N
N Little Rock	North Little Rock SD	Faulkner Lake WWTP	6	O
Barstow, CA	City of Barstow	Barstow Regional WWTP	2	N
Los Angeles	City of Los Angeles	Hyperion WWTP	400	C
Redwood City	South Bayside System Auth	South Bayside WWTP	19	O
Richardson Bay	Richardson Bay SD	Trestle Glen WWTP	0.1	N
San Bernardino	City of San Bernardino	San Bernardino WWTP No.2	14	O
Norwalk, CT	City of Norwalk	Norwalk WWTP	15	O
Stratford	Town of Stratford	Stratford WWTP	8	I
Torrington	City of Torrington	Torrington Main WWTP	6	N
West Haven	—	—	10	N
Elkhart, IN	City of Elkhart	Elkhart WWTP	17	I
Dubuque, IA	Dubuque Dept Public Wks	Dubuque WWTP	9	O
Kansas City, KS	City of Kansas City	Plant No. 20	7	O
Same	Same	Kan Point	25	O
New Orleans, LA	New Orleans St & W Dept	East Bank Plant	71	O
Ocean City, MD	Worchester Co. San Comm	Ocean City WWTP	7	O
Lynn, MA	City of Lynn	Lynn Regional WWTP	—	C
Swampscott	Town of Swampscott	Swampscott WWTP	2	N
Holland, MI	City of Holland	Holland WWTP	4	N
Port Huron	City of Port Huron	Port Huron WWTP	14	O
Independence, MO	City of Independance	—	8	—
Jefferson City	City of Jefferson City	Jefferson City WWTP	6	N
Cape Girardeau	—	—	—	—

Table I-5. *Fluidized-bed sludge incineration facilities in the U.S. (Continued)*

Major City or Area	Owning Authority	Plant Name	Flow (mgd = 43.8 L/S)	Status*
Omaha, NB	———	Papillion Creek WWTP	30	O
Lake Tahoe, NV	———	Round Hill WWTP	1	—
Pleasantville, NJ	———	———	—	—
Somerset-Raritan	———	———	15	O
Two Bridges	Pequannock-Lincoln Pk-Fairfield SA	———	70	O
Union Beach	Bayshore Regional Sew Auth	———	10	O
Waldwick	Northwest Bergen County	———	8	O
West Bedford	Gloucester Co Sewer Auth	———	20	O
Arlington, NY	———	———	—	—
Bath	———	———	—	—
Erie County	Erie County Sewer Agency	Southtowns WWTP	16	O
Hamburg	———	———	—	—
Little Falls	———	———	—	—
New Windsor	———	———	—	—
Oneida County	———	———	—	—
Port Washington	Port Washington	Port Washington WWTP	3	O
Poughkeepsie	———	———	—	—
Watertown	Arlington Sewer District		3	O
Shelby, NC	———	Shelby WWTP	4	O
Waynesville	———	Waynesville-Hazelwood	—	—
Franklin, OH	Warren County	———	—	—
Lorain	———	———	—	—
Downington, PA	Borough of Downington	Downington Regional WWTP	3	N
Hazelton	Greater Hazelton Auth	Hazelton WWTP	6	O
King of Prussia	Upper Merion Twp Auth	Trout Run WWTP	4	O
North Wales	Upper Gwynedd Twp Auth	Upper Gwynedd WWTP	2	N
Tyrone	Tyrone Borough Sewer Auth	Tyrone Borough WWTP	6	N

Table I-5. *Fluidized-bed sludge incineration facilities in the United States. (Continued)*

Major City or Area	Owning Authority	Plant Name	Flow (mgd = 43.8 L/S)	Status*
Clarksville, TN	City of Clarksville	Clarksville Main WWTP	5	O
Charlottesville, VA	———	———	—	—
Edmonds, WA	Edmonds PWD	Edmonds WWTP	4	O
Sheboygan, WI	———	———	—	—

* O = System is in operation regularly and used on a year-round basis.
N = System is not used; a more economical alternative is preferred.
I = System is used intermittently (low loading) or seasonally.
S = System is in startup status and not handling routine loading.
R = System is being remodeled or upgraded and has operated previously.
C = System is under construction.
- = No data available at this time.

Table 1-6. *Electric incineration facilities in the United States.*

Major City or Area	Owning Authority	Plant Name	Flow (mgd = 43.8 L/S)	Status*
Petersburg, AK	City of Petersburg	Petersburg STP	.80	N
Wrangell	City of Wrangell	Wrangell STP	.39	O
Decatur, GA	Dekalb County	Snapfinger STP	40	O
Gainesville	City of Gainesville	Flat Creek STP	14	O
Bay City, MI	Bay County	West Side Regional	32	N
Sylvan Beach, NY	Village of Sylvan Beach	East Oneida Lake STP	1.75	O
Cynthiana, KY	———	———	3.5	O
Greenville, TX	City of Greenville	Greenville STP	5.96	N
Plano	North Texas	Plano Rowlett Cr STP	6.88	O
Richardson	City of Richardson	Floyd Branch STP	1.90	N
Missouri City	Missouri City	Quail Valley STP	7.0	O
Aberdeen, WA	City of Aberdeen	Aberdeen STP	4.8	O

* O = System is in operation regularly and used on a year-round basis.
N = System is not used; a more economical alternative is preferred.
I = System is used intermittently (low loading) or seasonally.
S = System is in startup status and not handling routine loading.
R = System is being remodeled or upgraded and has operated previously.
C = System is under construction.
- = No data available at this time.

Table I-7. *Rotary kiln incineration facilities.*

Major City or Area	Owning Authority	Plant Name	Flow (mgd = 43.8 L/S)	Status*
Lake Arrowhead, CA	Lake Arrowhead Sewer Dist	Lake Arrowhead STP	.8	O
Holyoke, MA	Town of Holyoke	Holyoke STP	4.5	N

Table I-8. *Facilities combusting sludge in a refuse incinerator.*

Major City or Area	Owning Authority	Plant Name	Flow (mgd = 43.8 L/S)	Status*
Stamford, CT	City of Stamford	Stamford STP	19.4	O
Clayton County, GA	Clayton County Water Dept	Flint River STP	–	O
Glen Cove, NY	PPW of Glen Cove	Glen Cove STP	5.7	S

O = System is in operation regularly and used on a year-round basis.
N = System is not used; a more economical alternative is preferred.
I = System is used intermittently (low loading) or seasonally.
S = System is in startup status and not handling routine loading.
R = System is being remodeled or upgraded and has operated previously.
C = System is under construction.
- = No data available at this time.

Although MHFs were used for incineration of sludge long before the advent of the fluidized-bed incinerators, they are falling from favor. Because of the increasing severity of the requirements imposed for pollution prevention, the off-gases product can no longer be released to the atmosphere and substances that cause noxious odors must be decomposed at high temperatures before their discharge. As a result, with the MHF, the off-gases must either be recycled to the hot region of the incinerator or they must be led to separate burners operating at temperatures higher than 800°C (1,500°F). It is precisely this requirement that has been primarily responsible for the demise of the multiple-hearth incinerator.

Few multiple-hearth incinerators have been constructed recently, at least in West Germany, because the fuel costs involved in removing the odors from the flue gases often exceed the cost of incineration. Economic factors favor using the fluidized-bed incinerator, which has a high enough temperature to degrade the odors before emission to the atmosphere. The capacity of a multiple-hearth incinerator, expressed in terms of the dry solids in the sludge, is only about one-third of that of a fluidized-bed incinerator of comparable size.

Fluidized-bed incinerators in Germany are similar to U.S. designs. Controlled amounts of dewatered sludge are fed into the fluidized bed of sand, which is heated to 750°-850°C (1,400° -

Table I-9. *Total production of nonstabilized wastewater sludge. (In millions of cubic yards)*

	Amount		Percentage
Country	Generated	(Year)	Incinerated
Austria	—	—	—
Belgium	1.8	(1979)	1.7
Denmark	3.4	(1977)	9.0
Finland	3.1	(1977)	—
France	58.9	(1980)	15.0
Germany	98.1	(1980)	8.0
Greece	—	—	—
Ireland	0.5	(1980)	—
Italy	31.4	(1979)	5.0
Netherlands	5.2	(1979)	0.6
Norway	1.8	(1980)	—
Portugal	—	—	—
Sweden	6.3	(1978)	—
Switzerland	3.8	(1979)	9.5
Spain	—	—	—
Turkey	—	—	—
United Kingdom	48.4	(1980)	4.0
United States	160.9	(1980)	25.0

Cubic yards x 0.7646 = cubic meters.

1,600°F). The constituent water evaporates, the combustible substances burn in the bed or freeboard, and the combustion residues are swept out of the incinerator by the flue gases. The dust content of the flue gases may be as high as 200 g/m^3 (87 gr/cu.ft) and is reduced below the legally permissible level of 100 mg/m^3 (0.04 gr/cu.ft.) almost exclusively by electrostatic precipitators. In some cases, wet scrubbers have been installed to eliminate the gaseous pollutants (e.g., sulfur dioxide, hydrogen fluoride, and hydrogen chloride). The operating costs for fluidized-bed incinerators was about 300-500 DM ($114-$190) per ton of dry solids in 1983, including dewatering.

A combination of the multiple-hearth and fluidized-bed designs has been developed for the purpose of direct heat-transfer drying of sludge and removal of noxious odors from flue gases. This type of incinerator is equipped with a predrying and distribution zone that may have up to six hearths; the fluidized-bed chamber is located underneath. Forty to sixty percent of the water contained in the waste material is evaporated in the predrying zone; the vapors flow through the upper section of the combustion zone where all volatile components should burn out. Due to the highly effective drying operation, the needed cross section of the fluidized-bed zone becomes correspondingly smaller.

To ensure the maximum burnout of the flue gases, an after-burning chamber may be linked to this type of incinerator. In this type of plant, the combustion chamber may be kept even smaller with corresponding savings in capital costs.

Rotary kilns are comparatively expensive to install, and the capacity of units of similar size is much less than that of the MHF or FBF.

WASTEWATER SLUDGE INCINERATION IN JAPAN

Sludge incinerators were first installed in Japan in 1962. Table I-10 shows the number and type for 1977, 1981, and 1983 and illustrates that the multiple-hearth type is predominant both in number and in total incineration capacity. In particular, all incinerators with a capacity of 150 dry tons/ day (t/d) or more are MHFs. The largest size is rated at 300 wet tons per day, based on loading rates that are more conservative than those typical in the United States.

The percentage of total incinerating capacity accounted for by MHFs has dropped. In 1977 it was 89 percent, but in 1981 it was down to 84 percent. The share represented by FBFs has increased, and new types have recently been installed. These include wet oxidation, pyrolysis process, and melting furnaces.

The first installation of a fluidized-bed incinerator was in the early 1970s. Most of these are in smaller treatment plants that require intermittent operation due to low sludge production, and capacities are up to 100 tons per day, wet cake basis. Most of the plants that plan to construct new incinerators are smaller-size facilities, so the ratio of fluidized-bed units will grow larger in the future.

Rotary kilns and moving-bed type incinerators are seldom considered the most suitable design and are built only infrequently.

Table I-10. *The number and types of sludge incinerators in Japan.*

	1977			1981			1983
	No. of Units	No. of Plants	Capacity (tons/d)	No. of Units	No. of Plants	Capacity (tons/d)	No. of Units
Multiple-hearth	74	61	5,831	81	58	7,859	80
Fluidized-bed	9	8	305	21	6	164	13
Inclined grate, moving bed, and others	6	4	159	15	13	469	10
Process development units (PDU)							
Pyrolysis							5
Melting furnace							2
Wet oxidation							3

CHAPTER II. IMPROVING SLUDGE INCINERATION METHODS

INCINERATOR DESIGN PRACTICES

This chapter utilizes case studies to discuss how several operational problems were overcome at existing incineration facilities. The key to engineering these changes is the understanding of basic design considerations, since these remedial actions began with what amounted to redesigns. It is therefore necessary to present information required in the design of a typical incineration facility. Although the discussion that follows presents the design procedures for a multiple-hearth incineration process, many of the same concepts apply to other sludge combination processes as well.

Specifying the Feed

The first step in the design of a municipal sludge incineration system is defining the feed that the system must handle. The usual parameters are:

1. Feed rate - stated in kilograms (pounds) of wet-basis cake per hour

2. Properties of the feed -

    a. Percent solids (preferable to expressing as percent moisture)
    b. Percent combustibles in the solids (volatiles plus fixed carbon)
    c. Gross, or higher, heating value of the combustibles (HHV)
    d. Ultimate analysis of combustibles
    e. Presence of chemicals (e.g., lime) that react endothermically

Not often stated, but highly desirable, are softening and fusion points of the ash as determined by ASTM Method D-1857-68 if a representative sample of the sludge or ash can be obtained.

In many instances, precise information on the feed is not known when specifications are prepared. Instead, ranges of expected values are given to ensure that the furnace meets the needs of the wastewater treatment plant (WWTP). All too often the designer increases this uncertainty when communicating with the furnace manufacturer by specifying very wide and unrealistic ranges of values for the feed parameters. The numerical permutations and combinations that result from this practice prompt equipment designers to supply a single piece of equipment and expect it to operate over an unrealistic range of conditions. It is perhaps analogous to specifying a car for use in carrying a large family, pulling a camper on vacation and, at the same time, city driving, and getting 15 km/l (35 mpg) fuel economy. The responsibility for making a "best guesstimate" on the sludge feed and keeping this estimate within values that can be satisfied by a single-size piece of equipment is clearly the designer's.

An effective alternative to specifying ranges is to specify various possible modes of plant operation and then develop, for each of these modes, the two major parameters mentioned previously, feed rate and properties of the feed. One must then decide on:

- Minimum and maximum furnace exhaust temperature and

- Minimum percent oxygen in the exhaust gas or, in other words, the amount of excess air.

Prior to finalization of the specifications, heat and material balances should be prepared for each case. A summary table should indicate, as a minimum, the following items:

1. Sludge combustion air requirement - mass flow rate and volume rate, usually in kg/hr (lb/hr) and l/s (cfm)

    a. Shaft cooling air recycle
    b. Ambient air

2. Auxiliary fuel requirement - kJ/hr (Btu/hr) or in fuel volume terms

3. Auxiliary fuel combustion air requirement - units same as (1) above

4. Furnace exhaust flue gas volume - actual l/s (cfm)

After preparation of the summary table that indicates minimum and maximum values for each parameter, this table should be examined to determine if the adjustments required of the individual equipment items are within the useful operating range of the equipment.

A single factor applied to the quantity of sludge to be processed should be the sole basis for establishing the sizing of individual components. This will result in a harmonious design of all components of the system.

Understanding the Combustion Process

Problems in the incineration of sludge solids cannot be solved without a thorough and complete understanding of the combustion process. Although "hit or miss" approaches will occasionally yield the desired results, they cannot be relied on to keep a MHF—or any furnace—operating properly. The combustion control logic of a MHF is not understood by most engineers, and many furnaces in place today have been improperly designed; in addition, information contained in some operating manuals provided by manufacturers is inaccurate.

One approach to design is to consider that the MHF operates as a number of individual furnaces connected in series. The mechanical design (i.e., size and number of hearths; size, number, and location of burners; and size, number, and location of combustion air nozzles) and the combustion control logic should reflect this consideration.

The heat and material system balances that have traditionally been used as a basis of design for the MHF treat the MHF as a "black box." This is not to say that the First Law of Thermodynamics is invalid. The answers obtained by this "black box" approach certainly represent overall fuel and air requirements but do not give any clue to understanding the combustion processes occurring on the individual hearths. Without this understanding, it is impossible to determine, for example, the proper location of the auxiliary fuel burners. This usual approach gives the total heat required in the furnace, but installing one single large burner somewhere in the furnace would usually not represent an intelligent design. Additionally, the "black box" approach gives no clue as to the control loops necessary for control of the furnace.

"THERMAL JUMP" REVISITED

In the early years of municipal sludge incineration, the theory of the "thermal jump" derived from the work of Rudolphs and Baumgartner was used to justify a moderate exhaust temperature of nominal 430°C (800°F) in the gases leaving the furnace. Their paper stated that "distillation of volatile matters from sludge containing 25 percent solids did not occur until 80 to 90 percent of the moisture had been driven off, regardless of the temperature." Stated another way, starting with a 25 percent solids cake, volatilization should not occur until the total solids content of the sludge is between 63 and 77 percent.

More recent data indicate that self-sustaining combustion takes place when the mass reaches a total solids concentration as low as 48 percent. For combustion to occur, volatiles must be driven off, and, therefore, these data appear contradictory. This contradiction can be explained by a more detailed examination of the phenomena taking place within the MHF.

As the sludge proceeds on its downward, serpentine path through the MHF, moisture is continuously evaporated. The sludge on the hearth develops furrows caused by the action of the rabble teeth. When sufficient moisture has been evaporated, the very volatile parts of the sludge on the upper ridge of the furrow begin to undergo destructive distillation before they are turned over by the next pass of the rabble arm. The exact point at which this occurs is difficult to ascertain and is obviously affected by many variables. The previously mentioned value of 48 percent total solids is not an unreasonable estimate, however, *if it is recognized that this is an average value for all sludge within the hearth area, and the sludge on the upper ridges is substantially drier*.

Ideally, to ensure complete combustion, the hearth where these volatiles begin to distill off should have active combustion with visible flame and the hearth temperature should be 760°C (1,400°F) minimum. In addition, the volatiles should be exposed to this temperature for a defined length of time. Unfortunately, this is not always possible to achieve in actual practice. Certain organic materials called condensables may escape. The condensables and odors are the result of incomplete combustion of volatile organic compounds. These compounds are products of pyrolysis and materials distilled off from sludge during the drying process before the sludge reaches the active combustion hearth. The condensables are the material normally caught in the liquid impingement train of the EPA Method V particulate test, the fraction often referred to as the "back-half catch."

A number of MHFs operating with exhaust temperatures in the 400°C (800°F) range have had odor problems and have failed particulate emission tests because of the high contribution of the back-half catch. These problems have been corrected by:

1. Substantially increasing the temperature of the combustion (hottest) hearth, which in turn increases the temperature of the hearth immediately above the combustion hearth. This is where volatilization is most likely to occur, and sufficient temperature is provided in the gases to combust the distilled organics.

2. Providing an afterburner (either at the zero or top hearth or as an external unit), which operates at sufficient temperature (nominal 760°C [1,400°F]) to ensure complete combustion.

Of the two methods described above, the afterburner approach gives the greater degree of confidence, especially where there are low boiling organics present. Both methods imply the use of auxiliary fuel to reach a higher temperature in the gases. When a dewatered sludge with an adequately high total solids content is available, a 760°C (1,400°F) exhaust temperature can be achieved without the use of auxiliary fuel.

Furnace Operation

Incineration of sludge solids in an MHF occurs in four distinct zones (see Figure I-3):

1. Moisture evaporation;

2. Distillation and combustion of volatiles;
3. Combustion of fixed carbon; and
4. Ash cooling.

The boundary between zones may occur part-way across a given hearth. Assuming that the feed rate and thermodynamic properties of the sludge are a given (i.e., not subject to control), there are three primary variables that can be manipulated in a conventional-style MHF with all sludge combustion air going to the bottom hearth(s):

1. Flow rate of sludge combustion air;
2. Auxiliary fuel firing rate; and
3. Rotational speed of the rabble arms (rpm).

Thus, the following parameters are the controlled variables of the combustion process:

1. MHF exhaust temperature (temperature of the uppermost hearth prior to the effect of a zero-hearth afterburner or external afterburner);
2. Excess air in the MHF exhaust gas; and
3. Temperature of the combustion hearth.

Temperatures are usually measured by thermocouples, connected to appropriate instrumentation. There is no instrument called an excess air meter. What is actually measured is volume percent oxygen in the exhaust gas, either hot or cooled in a sampler. Measurement of hot flue gas containing much water vapor from sludge moisture and combustion products is termed "wet" basis. If, on the other hand, measurement is made on gases that have been cooled and scrubbed and have only residual moisture at 100 percent relative humidity, it is termed "dry" basis. Future discussions refer only to percent oxygen and, unless otherwise stated, this is on a "dry" basis. A handy reference formula for converting percent oxygen (dry basis) to excess air is:

$$\text{Percent Excess air} = [O_2/(21 - O_2)] \times 100$$

$$O_2 = \text{Percent oxygen (dry)}$$

The temperature of the combustion hearth is henceforth referred to as the temperature of the "hottest hearth."

A Look Inside a Multiple-Hearth Furnace

To fully appreciate why the conventional "black box" heat and material balances are inadequate for the design and evaluation of the MHF combustion process, it is necessary to examine the combustion process as it actually takes place. The results of a series of heat and material balances are shown graphically in Figures II-1 and II-2. Since these graphs are for comparative purposes only, it is advantageous to make certain simplifying assumptions.

- Assume shell heat loss is zero. Normally it amounts to only 2-3 percent.

- Assume all shaft and rabble arm cooling air is recycled back to the MHF as sludge combustion air. As a result there will be no net heat loss from the heated shaft cooling air being discharged to the atmosphere.

- Assume zero percent combustibles in the ash. Normally this value would be 1-4 percent.

For these calculations, two differently conditioned and dewatered sludges were chosen. One sludge was chemically conditioned (CCS) and the other was thermally conditioned (TCS). The thermodynamic properties of each follow.

	CCS	**TCS**
Percent total solids	25	40
Percent combustibles	65	60
Combustible heating value (kJ/kg combustibles)	23,000	26,000
Combustible ultimate analysis		
Carbon	50.64	53.73
Hydrogen	7.22	7.71
Oxygen	37.14	33.06
Nitrogen	5.00	5.50
Sulfur	0.00	0.00
TOTAL	100.00 percent	100.00 percent

In the graphs, the theoretical temperature of the products of combustion is plotted against percent total solids at 9.0 percent oxygen (75 percent excess air). The conventional "black box" heat and material balance would indicate, for the 25 percent total solids (TS), an exhaust temperature of approximately 450°C (850°F). However, if it is assumed that combustion begins when the TS reaches 50 percent, then the temperature on the hottest hearth (combustion hearth), where the 50 percent TS sludge is burning at 9.0 percent oxygen, should be approximately 980°C (1,800°F). Thus, what many have observed is shown graphically: the temperature of the hottest hearth is significantly higher than the exhaust temperature. A temperature of 980°C (1,800°F) would probably cause clinkers, and therefore the furnace operation would have to be modified.

Figures II-1 and II-2 also show the effect of operating at increased percent oxygen (excess air) in the flue gas. It is commonly stated in the literature that MHFs are operated at excess air rates in excess of 100 percent to assure oxygen for combustion. This large quantity of excess air is not required for complete combustion but is required to maintain the temperature of the hottest hearth at a level that will avoid clinkering or thermal stress to the furnace. Even though the desired result has been achieved in existing MHFs, the simplified approach used heretofore has prevented an adequate combustion control logic from being developed.

A value of 6.0 percent oxygen (40 percent excess air), under the proper combustion conditions of time, temperature, and turbulence, is sufficient for complete combustion. In Figure II-1 the temperature is plotted for values of 6.0 percent oxygen (40 percent excess air) and 0 percent oxygen (0 percent excess air). The problems of excessive temperatures on the combustion hearth are obvious in these situations relative to those with greater excess air. It is for this reason that where MHFs have been operated at nominally 6.0 percent oxygen (40 percent excess air) a starved-air combustion mode has been used.

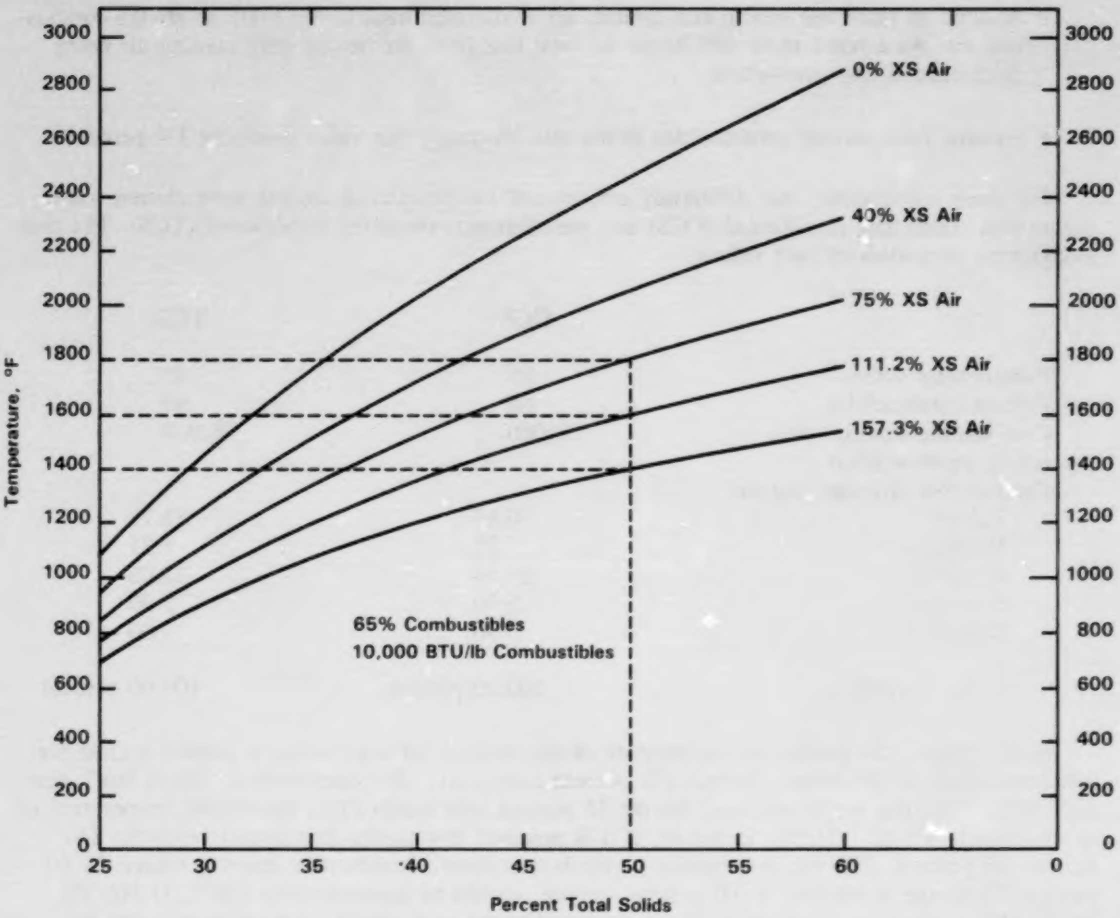


Figure II-1. Heat and material balances using 23,000 kJ/kg (10,000 Btu/lb) combustibles (°C = (°F - 32) 5/9).

Figure II-2 shows data for TCS. At 10.7 percent oxygen (103.3 percent excess air), the furnace exhaust temperature is 760 °C (1,400 °F), adequate to assure complete combustion and deodorization without the use of auxiliary fuel. Because of the ballasting effect of the high excess air, the temperature of the hottest hearth, at 50 percent TS, is approximately 870 °C (1,600 °F), or only 110 °C (200 °F) hotter than the exhaust temperature. Therefore, in a MHF with adequate air handling capacity, a TCS can be easier to incinerate.

Hearth-by-Hearth Balances

To perform a hearth-by-hearth heat and material balance, it is necessary to have an extensive data base to develop the ''rate and heat transfer equations'' that determine the success of any mathematical model of this type. Some information on these has been published, but most MHF manufacturers and knowledgeable consultants consider this information proprietary. Parameters that should be included in a hearth-by-hearth furnace simulation model are:

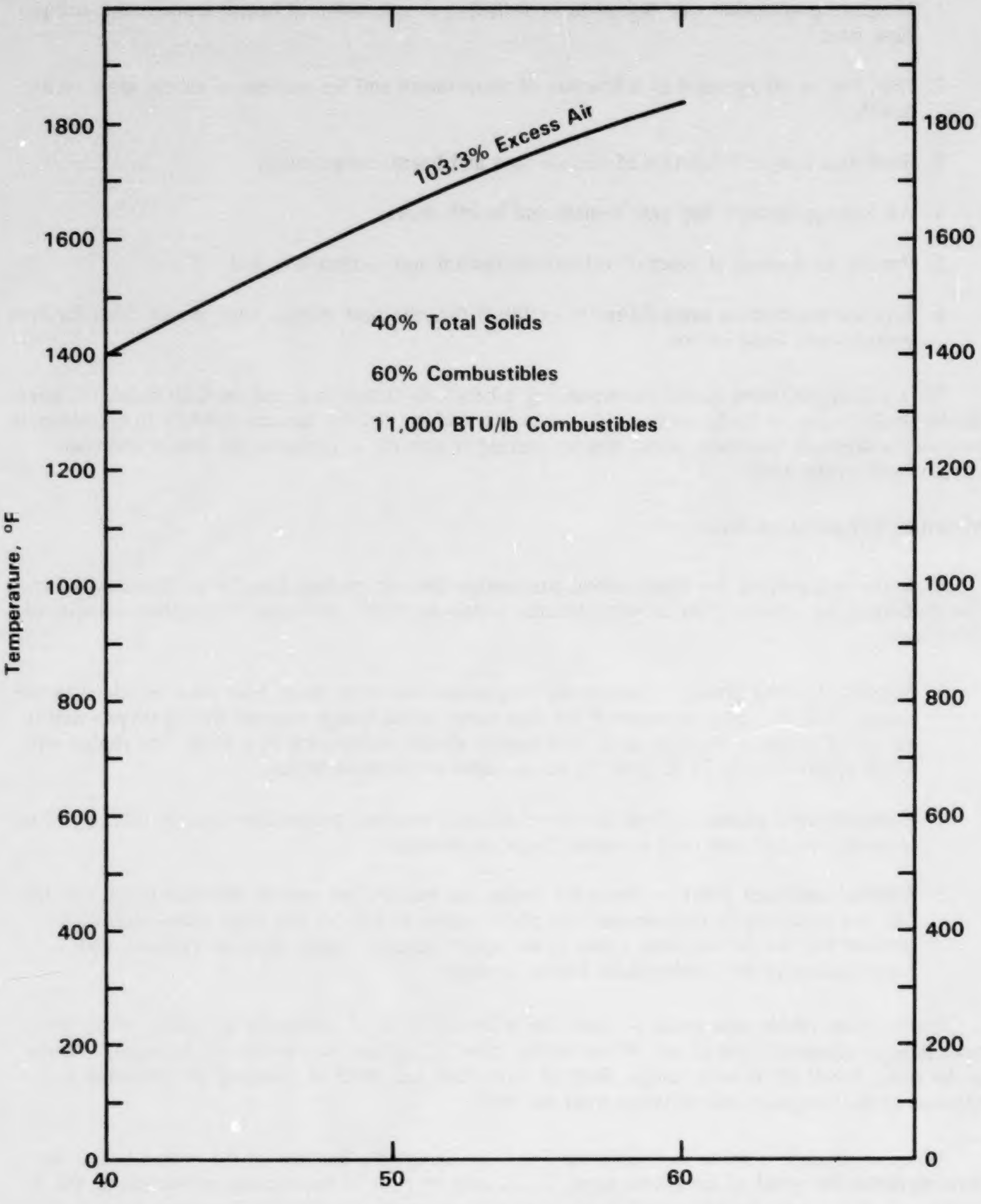


Figure II-2. Heat and material balances using 26,000 kJ/kg (11,000 Btu/lb) combustibles (°C = (°F - 32) 5/9).

1. Moisture evaporation rate (kg/m^2/hr or lb/ft^2/hr) as a function of hearth temperature and gas flow rate;
2. Heat loss to rabble arms as a function of temperature and the number of rabble arms on a hearth;
3. Shell heat loss as a function of surface area and hearth temperature;
4. Air leakage through flap gate feeders and hearth doors;
5. Percent total solids at onset of volatile distillation and combustion; and
6. Separate combustion rates (kJ/m^2/hr or Btu/ft^2/hr) and heat release rates (Btu/ft^{-3}/hr) for both volatiles and fixed carbon.

With a comprehensive model (incorporating a hearth-by-hearth heat and material balance), a sensitivity analysis can be made for the wide variety of sludges that the furnace is likely to encounter in a typical wastewater treatment plant, thereby making it possible to optimize the design and cost-effectiveness of the MHF.

Moisture Evaporation Rate

With the exception of the fixed carbon combustion and ash cooling hearths, moisture evaporation rate dominates the processes on all other hearths within the MHF. Moisture evaporation consists of three steps:

1. **Sensible heating phase** — Before any evaporation can take place, heat must be added to the sludge until the vapor pressure of the free water in the sludge exceeds the vapor pressure of the water vapor in the flue gases. For typical sludge incineration in a MHF, the sludge will reach approximately 71 °C (160 °F) before rapid evaporation begins.
2. **Constant rate phase** — Once the above phase is reached, evaporation usually takes place at a nearly constant rate over a certain range of moisture.
3. **Critical moisture point** — When the sludge has reached the critical moisture point, the drying rate occurring in the constant rate phase begins to fall. At this point (nominally 48-50 percent TS) the percent total solids in the upper ridges is higher than the average, and volatilization of the combustibles begins to occur.

An optimum rabble arm speed is where the width of the level portion in the valley of the furrows is approximately 3 cm (1 in). When rabble speed is too fast, this width will increase. When it is too slow, it will fill in with sludge. Both of these have the effect of reducing the projected area exposed to the hot gases and radiation from the roof.

When an attempt is made to "move the fire," or change the location of the hottest hearth by slowing down the speed of the rabble arms, it can only be done at the expense of increasing the inventory of sludge on a hearth, which can lead to a "runaway" (uncontrolled burning) furnace should this large inventory of sludge begin to burn. Additionally, volatilization is likely to occur on a hearth that is not up to proper combustion temperature (760 °C [1,400 °F] minimum), and unburned fuel gases, including tars and oils, will be discharged from the furnace (observed as smoke).

Attempts to control furnace operation by varying the speed of the rabble arms have largely proved unsatisfactory. Since a definite cause-and-effect relationship between rabble arm speed (manipulated variable) and any other controlled variable has never been satisfactorily established, rabble arm speed has been eliminated from the list of parameters considered in the hearth-by-hearth heat and material balance.

Combustion Control Logic

The importance of correct combustion control logic for a MHF has been stressed. A MHF control circuit developed from incorrect hypotheses cannot succeed. MHF operators should not be blamed for improper operation of their furnaces when they are not given the proper instruction and/or control system.

In seeking economical MHF operation, there are a number of variables that should be controlled:

- Temperature of flue gas leaving the furnace,
- Excess air (measured as percent oxygen),
- Temperature in the combustion hearth gases, and
- Location of the combustion hearth.

In a typical MHF fed at a constant rate, there are a number of conditions that can be manipulated to help keep the controlled variables at their set points:

- Mass flow rate of sludge combustion air (recycled shaft cooling air plus outside air),
- Rotational speed (rpm) of the central shaft,
- Firing rate (temperature set point) of auxiliary fuel burners, and
- Hearth location of burners currently firing.

In a typical MHF, with almost all of the sludge combustion air introduced in the bottom hearth, the combustion hearth is always the hottest hearth (HH). All hearths located above and below it are at lower temperatures.

It is desirable that the temperature of the HH *always* be maintained at set point temperature. Temperature control is achieved by varying the flow rate of sludge combustion air (SCA). In a stable burning mode, the flow rate of the SCA is *decreased* in order to *increase* HH temperature. Conversely, the flow rate of the SCA is *increased* in order to *decrease* HH temperature.

The maximum set point temperature for the HH is determined by either (1) the temperature, as measured at the wall, at which the sludge begins to form clinkers, typically 870° - 980°C (1,600° - 1,800°F) or (2) temperature limitation of the furnace, typically 1,000°C (1,900°F), which is based on the grade of firebrick used and the alloy in the rabble teeth. A further discussion of slagging and clinker formation is presented in Chapter III.

To maintain the burner flame safety circuit in a "purged" safety condition, a burner in the uppermost hearth that receives auxiliary fuel is always lit. Unless it is needed to provide additional heat to the furnace, this burner will remain on low fire.

For safety reasons, all burners should be turned ON by the MHF operator and not by the control system. When the combustion control logic circuit determines that a burner should be turned ON, a light on the control panel will signal the operator. The control panel lights, however, will also tell the operator WHICH burner should be started. The control circuit will automatically turn burners OFF.

When the combustion control logic circuit determines that more auxiliary fuel is needed in the furnace, it will signal the operator as to WHICH burner to light. Once this is done, the combustion control logic circuit varies the fuel firing rate until the desired results are achieved. The control circuit increases the fuel firing rate by AUTOMATICALLY *increasing* the burner set point temperature on the "selected" fired hearth. Conversely, when less auxiliary fuel is required, the control circuit AUTOMATICALLY *decreases* the burner set point temperature on the fired hearth, which in turn decreases the amount of auxiliary fuel being fired into the furnace. This type of control loop is commonly called cascade control.

The maximum *set point temperature* for any fired hearth should be at least 50°C (100°F) less than the *set point temperature* of the HH. This avoids control circuit problems by assuring that the control logic will not confuse a fired hearth with the HH.

DEWATERING SLUDGE

Many processes are available for removing water from sludge (dewatering) and thus preparing it for combustion. Each of these processes can be designed in various ways, make use of different commercial equipment, and be operated in alternative modes. Their objective is to ultimately produce a high-solids cake and thereby minimize auxiliary fuel usage in the subsequent combustion process.

Thickening, conditioning, and dewatering are the common processes for removing water from sludges. Other processes such as drying and dehydration are less common. Some processes (like composting and combustion) result in water removal, but that is not ordinarily their primary purpose.

Dewatering of sludge to produce a feed to the incinerator is a critical step for the process of combustion. Both centrifugal and filter-type dewatering equipment have been greatly improved in recent years. It no longer holds true that incineration is an unreasonable consumer of fuel. Many incinerators today operate in an "autogenous" mode, using no fuel for moisture evaporation at all.

The burning quality or heat content of a sludge as fed to an incinerator may principally be improved in three ways:

1. Remove water from the sludge more effectively by using the best available type of dewatering equipment with the most appropriate conditioning process.
2. Before feeding sludge to the incinerator, dry the sludge partially or completely, in addition to dewatering it, by using the heat from combustion that would otherwise be wasted.
3. Add a combustible material to either the dewatered or undewatered sludge as an augmentation of its heat value in relation to its moisture.

Dewatering Equipment

The most common approach is to design new facilities with the latest and most cost-effective type of dewatering machine. In centrifuges, this is currently the variable-speed backdrive type that has reached the market in the past decade. In filtering equipment, the continuous-belt filter press has taken a major share of the market once held by the vacuum drum filter. Another filtering method is the recessed plate filter press, which was adapted from the chemical industry and is commonly provided in an automated version.

A strong endorsement of the belt press comes from the city of Hartford, CT. Similarly, dramatic improvements in dewatering with the belt press were reported by the wastewater treatment plants in Rochester, NY, and Duluth, MN. In these cases, the substitution was for rotary vacuum drum filters. Some plants that have attempted to use continuous-belt filter presses in lieu of centrifuges, however, have reported dissatisfaction with performance; examples of this are: Philadelphia Southwest, Denver Metro, and Central Contra Costa in California. The principal problem with the belt press arises when the sludge feed varies in quality and this causes a change in the required polymer dose. The operator must be alert to such changes and modify the dose to meet the new condition. Failure to do this results in the sludge being squeezed out at the sides and causes a severe housekeeping problem. A centrifuge will give more solids in the centrate and a wetter cake in the same situation but not cause a housekeeping problem.

Carver-Greenfield Dewatering (Drying) Process

The Carver-Greenfield (C-G) process was developed specifically for application to "liquid-solid" slurries and has been successfully applied to various industrial slurries as well as industrial and municipal wastewater treatment plant sludges. In the C-G process, water is essentially extracted from sludge using a multiple-effect evaporator or vapor recompression dryer that results in a considerable economy of steam compared to single-effect heat dryers.

A schematic diagram of the process as designed for the Hyperion Energy Recovery System (HERS) in Los Angeles, CA, is presented in Figure II-3. Dewatered sludge is first mixed with an oil, such as light-high boiling solvent, which serves as a carrying or fluidizing medium. The carrying oil assures that fluidity is maintained in all phases of the evaporation cycle and that formation of scale or corrosion of the heat exchangers is minimized. Sludge-oil slurry is then pumped to a multiple-effect evaporator where water is vaporized. The remaining solids-oil mixture is then centrifuged and hydro-extracted (i.e., steam stripped) to separate the carrying oil from the solids.Carrying oil is recycled for reuse in the evaporative cycle while the solids are removed for other purposes, including subsequent combustion or reuse in agriculture. Oil and grease content (i.e., freon or hexane extractables) of the Hyperion sludge varies from about 8 to 15 percent of the dry sludge solid weight. These nonpolar components dissolve in the carrying oil. A sidestream of the carrying oil is continuously withdrawn from the C-G evaporator and distilled to separate light fluidizing oil from higher-molecular-weight sludge oils. Fluidizing oil is returned to the C-G process, and the sludge oil is stored for subsequent combustion in the fluidized-bed gasifier. Startup of the Los Angeles HERS System is scheduled for late 1985, with full operation in early 1986.

Continuous Belt Filter Press

Hartford, CT, Case History. Hartford, CT, began pilot testing belt filter presses in the spring of 1978. Test results showed that significantly drier sludge cake was produced at a higher production rate with a belt filter press (BFP) than could be accomplished with the existing vacuum filters. The plant staff then conducted side-by-side performance tests of the best performing BFPs to select the first BFP for procurement and installation. The first BFP was installed in 1979 and its startup and shakedown were carefully monitored. Despite numerous mechanical problems and excessive downtime (25 percent), the BFP quickly performed so cost effectively that approval for acquiring a second press was granted only 4 months after installation of the first one. The payback period for the first press was only 6 weeks. In selecting the second BFP, performance tests were again con-

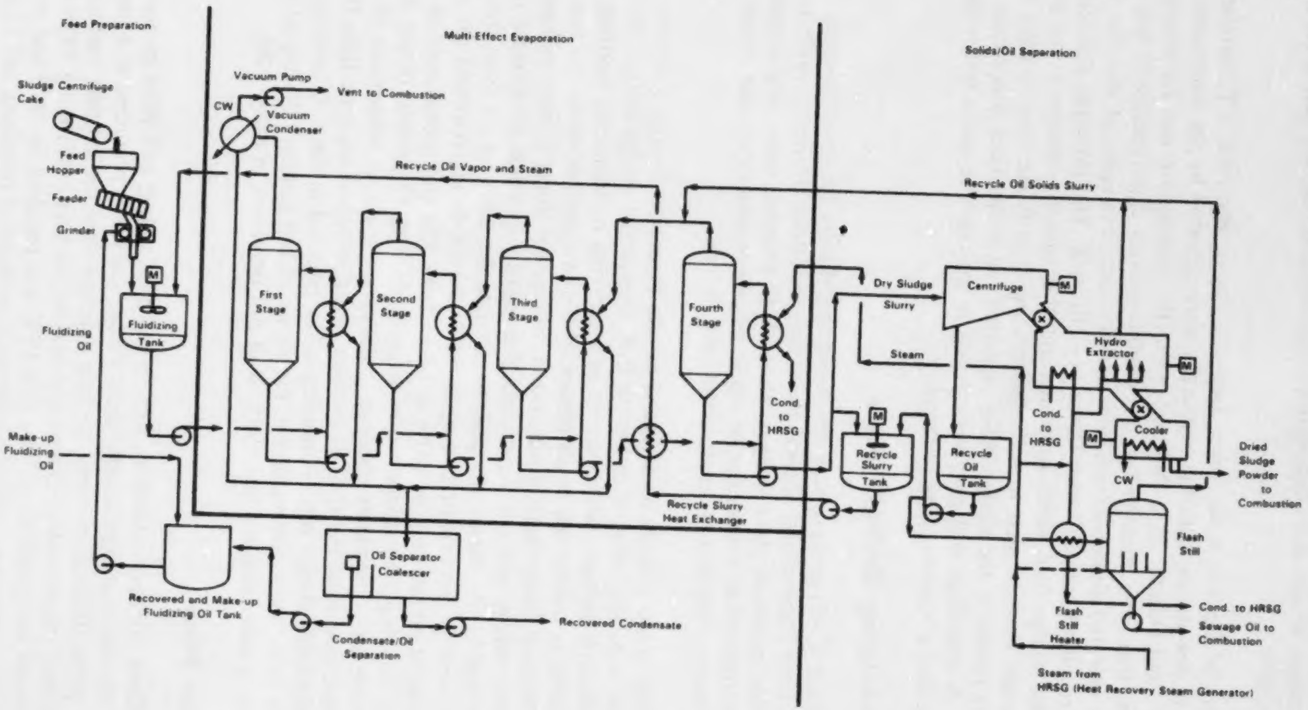

Feed Preparation
Multi Effect Evaporation
Solids/Oil Separation
Sludge Centrifuge Cake
Feed Hopper
Feeder
Grinder
M
Fluidizing Tank
Fluidizing Oil
Make-up Fluidizing Oil
Vacuum Pump
Vent to Combustion
CW
Vacuum Condenser
Recycle Oil Vapor and Steam
Recycle Oil Solids Slurry
First Stage
Second Stage
Third Stage
Fourth Stage
Cond to HRSG
Recycle Slurry Heat Exchanger
Recovered and Make-up Fluidizing Oil Tank
Oil Separator Coalescer
Condensate/Oil Separation
Recovered Condensate
Dry Sludge Slurry
Steam
Centrifuge
M
Hydro Extractor
M
Cond. to HRSG
M
Cooler
CW
Recycle Slurry Tank
M
Recycle Oil Tank
Dried Sludge Powder to Combustion
Flash Still
Flash Still Heater
Cond. to HRSG
Sewage Oil to Combustion
Steam from HRSG (Heat Recovery Steam Generator)

Figure II-3. Schematic process diagram for a four-evaporative-effect Carver-Greenfield process as designed for the Hyperion Energy Recovery System.

ducted to evaluate overall performance, mechanical design, and maintenance features of competitive presses and to incorporate the most desirable requirements into the bid specifications. The second BFP was supplied by a different manufacturer than the first one and was installed in December 1979, just 8 months after the first one.

Since Hartford was one of the first plants to try the BFP, operational difficulties were expected. Initial BFP operation included problems with the bearings, spray water pump, filter screen cleaning, filter screen tracking, and filter screen seam closures. With assistance from the manufacturer, the first press was retrofitted and upgraded for more reliable operation. The second through fourth BFPs were from a different supplier and had fewer mechanical problems.

As more experience was gained, improvements were made in several key operating conditions. Filter screen seam closure wearing was reduced by using scraper blades of a higher molecular weight plastic, and an increase of from 500 hours to an average of 1,500 hours of filter screen operating life resulted. Proper polymer conditioning of the sludge was a problem on all the BFPs. A two-component liquid polymer mix was developed in experiments by a polymer supplier to reduce dosage requirements to the same level as was required for the vacuum filters. Changes in the sludge conditioning tank to improve polymer/sludge mixing also helped reduce dosage requirements and increased operational flexibility for adjusting to the sludge's variable characteristics. Maintaining a constant BFP feed by mixing the raw primary and waste-activated sludges from three plants requires close operator control. Sludge blend variations of only 5-10 percent can cause a press screen plug, resulting in sludge squeezing out at the ends of the rollers. This results in a reduction in cake solids, lost production, and a messy cleanup job. In spite of these operating problems associated with reducing a new operating technology to routine production line practice, the operational improvements and cost savings achieved with the BFPs at Hartford were dramatic.

Energy savings realized from the BFP conversion were significant. From the time of the plant's startup in 1972, the activated-sludge mixed-liquor suspended solids (MLSS) concentration had averaged 4,000-5,000 mg/l, requiring approximately 32.8 m^3/s (100 million cubic feet per day) of dissolved air. With the BFPs, the increase in dewatered sludge production has enabled the MLSS level to be lowered to a more desirable 2,000 mg/l range. The resulting decrease in the dissolved oxygen demand reduced the daily air usage to approximately 18 m^3/s (55 million cubic feet per day). This reduction, in turn, reduced the electrical energy requirements of a 2,238 kW (3,000 hp) air compressor by 20 percent, which amounted to a $200,000 per year savings in electricity costs. Also, each vacuum filter had a 53.3 kW (71.5 hp) requirement as compared to 16.4 kW (22 hp) for each belt press. This reduction in electrical use resulted in an estimated savings of $25,000 per year. In addition, the elimination of the vacuum pumps resulted in a maintenance savings of $6,000 per year. In total, these savings amounted to $231,000 per year.

The average specific fuel consumption or gallons of oil per dry ton (dt) sludge solids and the moisture-to-volatile (M/V) ratio for the Hartford incinerator operations for the years 1978-81 are shown in Table II-1.

The savings resulting from the belt filter presses are reflected in the sharp reduction in the sludge cake M/V ratio, particularly in 1980 when the major fuel reduction was achieved. The net reduction of an average of almost 0.34 1/kg (82 gal/dt) of oil would translate into savings of over $3.21 \times 10^3 m^3$ (848,000 gal) of oil at the 1982 dry ton production level of 9.41×10^6 kilograms (10,351 tons). Coupled with the dramatic reduction in fuel consumption, there was also a 57 percent gain in the volatile solids incineration rate per operating equipment hour, which is the key production performance parameter. Furthermore, the average incinerator hours of operation per day for two incinerators also dropped from 46.5 in 1978 to 35.7 in 1981, a 23 percent decrease. This meant that only two of the three plant incinerators had to be used routinely.

Table II-1. *Moisture-to-volatile ratio for Hartford incinerator operations.*

Variable	Year 1978	1979	1980	1981	Percent change (1978-81)
Percent solids	13.8	14.5	18.5	19.5	+ 4
Sludge cake M/V	8.6	8.1	5.8	5.4	− 37
Fuel consumption (gal/dt)[1]	125.2	116.1	60.5	43.5	− 65
Incineration rate (volatile tons/ incinerator/hr)[2]	0.7	0.7	1.0	1.1	+ 57

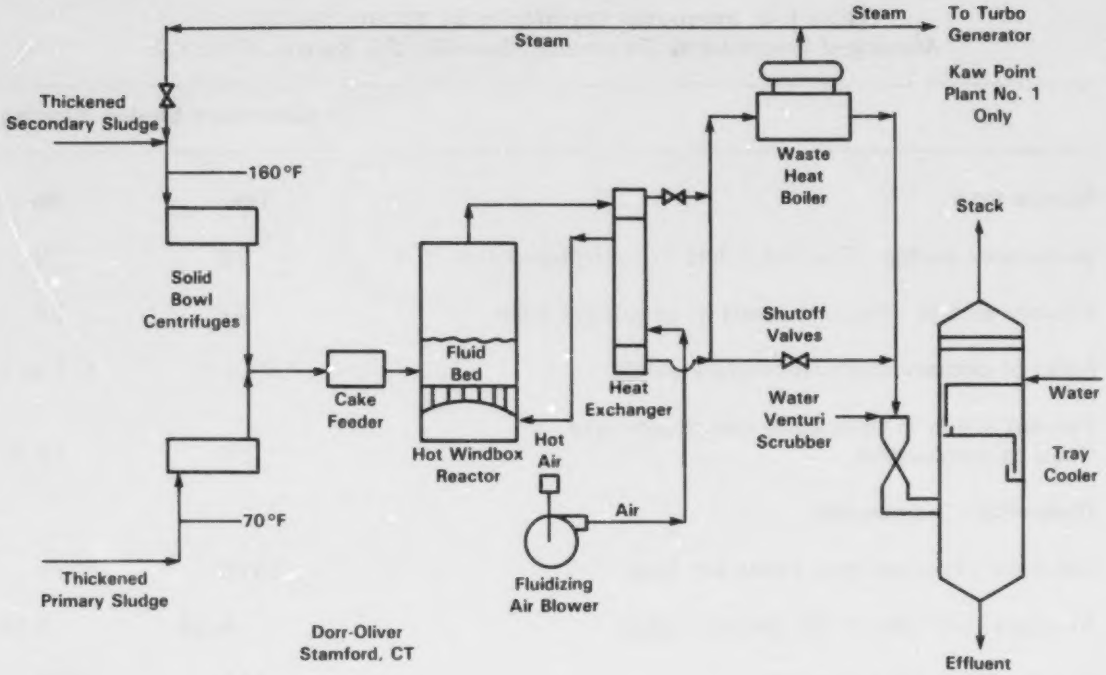
[1] gal/dt = 0.004 1/kg
[2] t/hr = 907.2 kg/min

These substantial results were accomplished after a considerable amount of time and effort was invested by the Hartford plant management, staff, and operating personnel. The experience of Hartford with the belt filter presses serves as a classic example of the opportunities that exist in many plants throughout the country to achieve cost-effective performance by the adoption and modification of new operating technologies.

Improvement of Centrifugal Dewatering by Steam Injection

Kansas City, KS, Case History. Municipal Wastewater Treatment Plant No. 1 is located southwest of downtown Kansas City and situated on the Kansas River. The design flow is 0.3 m^3/s (7 mgd) with potential to expand to a maximum of 0.92 m^3/s (21 mgd). Plant No. 20 is a complete mix-activated, sludge-type secondary treatment plant with aerobic sludge digestion and sludge incineration. The flow diagram for the wastewater treatment process is shown in Figure II-4.

Typically, secondary sludge alone will mechanically dewater to cake solids of 10-14 percent. Following extensive testing and development work at Northwest Bergen County WWTP in Waldwick, NJ, a centrifugal dewatering system was provided at Kansas City, employing steam heating of the secondary sludge and an eddy current back-drive for the centrifuge. Steam was used to heat the secondary sludge to 73.9°C (165°F) just ahead of the centrifuge. The eddy current back-drive for the centrifuge automatically adjusts the differential speed between the bowl and the scroll to maximize solids' residence time in the centrifuge and to keep the centrifuge operating at full load regardless of percent sludge solids in the incoming feed. It is not known if this sludge heating with steam can be universally applied to all secondary or activated sludges. It certainly worked well at Kansas City Plant No. 20, as shown in Table II-2. The fire tube boiler is designed for an operating pressure of 700 kPa (100 psig). It is normally operated at 400 kPa (60 psig), as this is all that is required for steam injection into the sludge feed line to the centrifuge. Also, operation much below 400 kPa (60 psig) (saturated steam 153°C [307°F]) is not recommended because of potential corrosion problems at lower steam pressures and temperatures. The steam requirement at Kansas City Plant No. 20 for the conditions specified in Table II-2 and Figure II-4 is 1,114 kg/hr (2,455 lb/hr) of 400 kPa (60 psig) saturated steam. The fire tube boiler is rated at 1,800 kg/hr (4,000 lb/hr), so some hot gas is bypassed around the boiler to balance the steam supply with steam demand.


Steam
To Turbo Generator
Steam
Kaw Point Plant No. 1 Only
Thickened Secondary Sludge
160°F
Waste Heat Boiler
Stack
Solid Bowl Centrifuges
Shutoff Valves
Fluid Bed
Heat Exchanger
Water Venturi Scrubber
Water
Cake Feeder
Hot Windbox Reactor
Hot Air
Tray Cooler
Air
70°F
Thickened Primary Sludge
Fluidizing Air Blower
Effluent

Dorr-Oliver
Stamford, CT

Figure II-4. Municipal Wastewater Treatment Plant No. 1, Kansas City, KS.

DRYING SLUDGE BEFORE COMBUSTION

Drying the sludge before incineration has not been adopted in the United States, except where cocombustion of sludge and solid wastes is the objective. Stamford, CT, has done this successfully in a rotary dryer for several years (see Chapter III). Attempts at Harrisburg, PA, to use a "porcupine" dryer have been unsuccessful, although this unit has worked satisfactorily in Europe. At the Flint River WWTP in Clayton County, GA, the Heil dryer is used and the sludge is pelletized.

Two examples of systems for combustion sludge that is burned by itself are located at plants in Minneapolis-St. Paul, MN, and Norwalk, CT. At the Metro WWTP serving the Twin Cities, two rotary dryers were provided in the facilities started up in 1983 to provide a dry sludge option in case a potential offsite use was developed or if very wet feed was being delivered from the sludge dewatering system. As of this time, these dryers have not been used. Because thermally-conditioned sludge is developed very effectively, the main operating problem has been too "hot" a feed to the furnaces, instead of excess moisture. At the Norwalk plant, an add-on dryer system of the fluidized-bed type was started up in 1983 and is reported to be operating successfully. This system links the previously installed Fluosolids® combustor with the new dryer by lifting hot sand to the dryer, where the feed sludge becomes mixed with the sand. The now-dried sludge solids mixed with sand are dropped back to the main combustion chamber and burned. A further linkage of the two vessels is that the fluidizing air for the dryer is heated in the second stage of the air preheater that extracts energy from the hot combustion gases. The first stage provides a hot air stream to the windbox of the combustor. The benefit of such integration is savings in fuel. The water is taken away from the

Table II-2. *Improving dewatering by stream injection—Municipal Wastewater Treatment Plant No. 20, Kansas City, KS.*

	Secondary Sludge Heating	
Sludge feed	**Yes**	**No**
Secondary sludge - Percent solids in centrifuge cake	23	12
Primary sludge - Percent solids in centrifuge cake	27	27
Ratio of primary solids/secondary solids	1.7 to 1	1.7 to 1
Percent solids in composite centrifuge cake (feed to combustor)	25	18.5
Fluosolids® combustor		
Capacity - Pounds feed solids per hour	1415	1079
Auxiliary fuel - Btu x 10^6 per ton solids	4.18	8.56
Power - kWh per ton solids	290	380
Operating costs (47.4 tons/solids per week)		
Operator hours/week - shifts/week	72-9	96-12
Operator labor cost ($25,000/year/person) dollars/ton solids	19.78	$26.37
Auxiliary fuel cost ($5/million Btu) - dollars/ton solids	$20.90	$42.81
Power cost (5¢ per kWh) - dollars/ton solids	$14.50	$19.00
Total labor, fuel, and power	$55.18	$88.18
Savings per ton of solids	$33.00	
Annual savings (2,275 tons/year solids)	$75,000	

1 kg = 2.20462 lb   1 kJ = 0.948 Btu   1 Mg = 1.1023 ton

sludge solids at a much lower "cost" in calories per gram (Btu's per pound) of water than it would be in the combustor. The moist off-gas leaves the dryer at a much lower temperature, perhaps 100° - 130°C (220° - 260°F), than it would if the drying was being done in the main combustor. This moist, odorous gas is then wet-scrubbed to remove its moisture burden before being routed back through the first stage of the preheater to the main combustor windbox and into the combustor, where any remaining odors are destroyed.

Another major benefit of the Norwalk installation, as there would be with any predrying process, is that the capacity of the combustion device is expanded greatly. Much larger amounts of sludge solids can be burned per hour because the limitation caused by necessary drying in part of the combustion unit is no longer present. At Norwalk the burning capacity was doubled. Thus, a plant with a sludge disposal load in excess of its burning capacity might find that adding a predrying step expands its capability and reduces fuel consumption per unit of solids handled at a much lower cost than if it elected to add another combustion system.

Drying ahead of combustion, of course, is not new. It has been practiced at Allegheny County Sanitary District's plant (Alcosan) in Pittsburgh, PA, for many years, as well as in other locations with Raymond-type flash dryer equipment that is linked to a combustor.

Energy-Efficient Dehydration Prior to Combustion

Heat drying to remove moisture prior to combustion, as discussed in the previous sections, can be accomplished in a number of different ways. It can be thermodynamically advantageous provided that the moisture is removed with less energy than that required to accomplish the same thing in a furnace. Two heat drying processes are examined here: indirect contact steam dryers and the C-G multiple-effect evaporation process. Other drying systems are available but generally require greater energy input than the two examined here.

An energy balance for indirect steam drying shows that the thermal requirement for drying is about 2,910 kJ/kg (1,250 Btu/lb) of water removed, which equates to 99,000 MJ/day (94 MBtu/day) if it is assumed that the sludge is dried to 80 percent solids. Energy recovery from the furnace exhaust is about 77.2 percent of input, or about 104,430 MJ/day (99 MBtu/day). Recovered energy essentially balances the requirement of the steam dryers. Net energy cannot be recovered unless the cake solids concentration is significantly increased above the 20 percent assumed.

A four-effect C-G process will thermodynamically operate at about 930 kJ/kg (400 Btu/lb) of water removed and produce a product with about 1 percent moisture. An energy balance for C-G drying and combustion shows that 24,000 MJ/day (32 MBtu/day) is required for the C-G process and about 111,000 MJ/day (105 MBtu/day) is recovered from the combustion system; thus, significant net energy production can be accomplished even with 20 percent sludge solids.

Energy-efficient dehydration of wet sludge cake can produce a material capable of autogenous combustion without the need for supplemental fuels. Sufficient steam can, in some cases, be generated from thermal processing for net electrical power production as well as operation of the drying process. Importation of fossil or alternative fuels to the treatment plant site is not required, and the technology involved appears to have a low odor potential compared to other alternatives. For these reasons, energy-efficient drying of digested, dewatered sludge using the C-G process was selected by the city of Los Angeles.

Other Drying Methods

In addition to the use of hot gases from the incinerator in external direct or indirect drying devices, other interesting developments in promoting more efficient drying within the incinerator have taken place in Germany and Japan.

In Germany, several "hybrid" furnaces have been built that combine the fluidized-bed and the multiple-hearth configurations in one shell. The MHF portion is above, and the combustion region is below. Partially dried cake drops into the fluidized bed and is burned with minimal fuel demand. Also, the diameter of the fluidized bed is lowered by this design because it is not evaporation-limited. Two such Lurgi furnaces have been in service in the Frankfurt treatment plant for several years.

In Japan, studies have been carried out in experimental systems where gas is recirculated through the drying zone to increase velocity over the sludge and increase the rate of evaporation. This was found necessary in units operated in the starved-air combustion (SAC) mode because of the low excess air supply, which in turn was intended to minimize the oxidation of chromium to the hexavalent state, the most toxic form. One or two of the hearths are actually operated in reducing conditions for this purpose, which in turn mandates the lesser air supply. This technology is expected to become increasingly popular in Japan and those parts of the United States with sludges high in trivalent chrome.

FUEL NEEDS

Stable operation of a sludge solids combustor requires an equalization between heat in and heat out; this is known as a heat balance. Heat in can be in the form of sensible heat energy and introduced in the air supply, which is at an elevated temperature, or in the combustible material. Heat out can be as sensible heat energy contained in combustion products, latent heat of water vaporization, radiation and surface losses, and heat that is lost in excess air and equipment cooling. The balance point is dependent on the amount of excess air that is allowed to pass through the furnace and the recovery of energy from the gases leaving the furnace. A system requiring no heat other than what is provided by the sludge cake is termed autogenous.

A furnace being fed sludge cake that does not have sufficient fuel value to balance the heat leaving the system requires auxiliary heat to stay in balance. This is supplied by burners using commercial fuel such as natural gas or fuel oil, which is fired into the furnace to inject heat.

Sludge cake that has an excess of heat content, as compared with the heat needed for drying and elevating the combustion gas stream to target flue gas temperature, is termed superautogenous. If superautogenous burning is conducted at high temperatures, equipment damage and ash fusion can occur. Control of the temperature can be achieved by varying the air supply or by modifying the cake moisture.

Fuel is not used in a sludge incinerator to burn sludge—it is burned to evaporate water. Any sludge cake will burn by itself once it gets dry enough. Fossil fuel is only used to remove most of the water, but sludge solids do not have to be bone dry to burn; self-sustaining combustion will occur on a sludge lump once it gets to about 50 percent moisture or less as was discussed in an earlier section. Frequently, dewatering sludge to a higher solids content is more economical than using fuel in the incinerator to evaporate water.

Fuel is also needed for other reasons:

1. Startup heating and holding at standby of a furnace requires fuel that cannot be furnished by sludge combustibles. Cooldown may require some fuel to manage the rate of temperature drop.

2. Safety standards may require that at least one burner is firing at all times.

3. If a mandatory exit temperature is required by air quality permit or policy of plant management, some fuel may be required to assure compliance with this requirement.

Heat sources that can be used to supplement the sludge combustibles to achieve heat balance at the desired furnace exit temperature and oxygen levels are found in Table II-3.

Table II-3. *Supplemental energy sources.*

Source	Comment
Natural gas	Sometimes only available on an interruptible basis; normally the lowest cost fuel
Fuel oil	More expensive than gas
Air	"Hot" air from the MHF shaft cooling system exhaust; preheated air from the fluidized-bed windbox
Scum	Requires a special concentrator for waste removal and a metering pump for controlled feeding
Coal	Requires dustproof construction within the plant for handling; must use gas or oil for MHF temperature control
Waste oil	Practical if a source of reasonable, steady volume is available. Concern must be exercised regarding handling and contaminants
Refuse-derived fuel (RDF)	A potential fuel; has not yet been successfully used
Woodmill waste or wood chips	Possible handling problems (bridging in bulk bias); wood chips have been used successfully in FBFs
Paper mill waste	May contain a high ash level due to filler
Industrial oily wastes	Not recommended because of potential toxic emissions and corrosion to ducts and scrubber system
Repulped paper	Water on the fibers may nullify heat gain from cellulose; requires dewatering and mixing with sludge

Understanding Incineration to Minimize Fuel Needs

Fluidized-Bed Incineration at Duffin Creek, Toronto. On the north shore of Lake Ontario, east of metropolitan Toronto, the first stage of one of Ontario's largest sewage treatment plants is in operation. The Duffin Creek Water Pollution Control Plant is being built in four stages. Stage 1 has a daily treatment capacity of 289,250 m³ (50 mgd). The sludge combustion and energy recovery system at this plant is a set of parallel trains of fluidized-bed combustors, each rated at 67 × 10^6 kJ/hr (63 × 10^6 Btu/hr).

This combustion facility has several interesting and innovative features. The fluidized-bed reactors are designed to operate either as CWB or HWB units. The exhaust gas-to-air heat exchanger is piped so that it can be bypassed or so that a part or all of the reactor hot gases flow through the heat exchanger. This means that the fluidizing combustion air to the reactor can be controlled from about 60°C (140°F) (heat developed by compression in the blower) with no air preheating when burning drier sludges, up to a maximum air preheat of 621°C (1,150°F) when burning wetter sludges. Part of the steam generated in the water-tube waste heat boiler is used in a turbine to drive the fluidizing air blower. The balance of the steam is used for process steam and for building heating. In the future, when three more stages are added and plant capacity has increased, turbo generators will be added to produce electrical energy that will be used in the wastewater treatment plant. Venturi scrubber effluent with collected ash is thickened and then dewatered. Thickener overflow is recycled to the Venturi scrubber. Dewatered ash is blended with dry ash from the waste heat boiler dust hoppers to produce a damp ash material that is trucked to a landfill.

Successful performance testing was carried out on the system in January 1982. Air quality test data and operating conditions during testing showed that total hydrocarbons in the stack ranged from 2 to 7 ppm and averaged 4.5 ppm; stack particulates were 0.13 gm/kg (0.25 lb/ton) of feed solids; combustibles in the ash were less than 1 percent. To verify the adequacy of the installation, higher solids cake was imported from the nearby Lakeview plant. This thermally conditioned sludge filter cake was 34-36 percent solids, and the performance was satisfactory; no fuel was required.

In early 1983, the Duffin Creek Plant was operating at reduced capacity. The belt filters were not producing the projected 30 percent cake solids but rather cake solids ranging from 17 to 27 percent and averaging about 20 to 22 percent. Also, the amount of volatile solids in the sludge was below the design level. Because of the higher water content of the sludge and the lower volatile solid content of the sludge solids, it became desirable and necessary to maximally preheat the air to a temperature of 621°C (1,150°F) so as to minimize the auxiliary fuel requirement. With increased air pre-heating, the gas temperature to the waste heat boiler was lower, resulting in reduced steam production. When burning a 22 percent solids concentration sludge of which 70 percent of the solids are volatile, the auxiliary fuel requirement goes from 0 to 0.14 liters of No. 2 oil per kg of solids (0 to 34 gal/ton). The combustor capacity drops from a design of 4,350 to 3,570 kg/hr (9,600 to 7,860 lb/hr). Steam production drops from a design value of 11,750 to 10,054 kg/hr (25,906 to 22,165 lb/hr). The fluidizing air blower consumes the same amount of steam, 4,470 kg/hr (9,850 lb/hr) in both cases, but in terms of percentage of total steam generated, steam usage goes from 38 percent of the total to 44 percent of the total. Tests were carried out with other belt presses for sludge dewatering. These newer units in tests produced 4 to 5 percent higher solids content than is being obtained with the existing units. These drier cakes, coupled with increased sludge generation rates, reduced the usage of auxiliary fuel and thus reduced operating costs, but this was not considered sufficient. In October 1983, purchasing commitments were made for membrane-type automatic plate-and-frame filter presses.

UPGRADING EXISTING MHFs TO REDUCE FUEL NEEDS

Of the various types of combustors in common use, two offer the opportunity to make the drying process more efficient and two do not. Those that do are the MHF and the IEF. Both the MHF and the IEF configurations provide a long residence time for the solids and permit separation of the drying and burning zones for stagewise process control, a feature that is not possible in a FBF and difficult in a rotary kiln furnace.

A major improvement in using the MHF as a better drying device came through a study at the city of Indianapolis's Belmont Street Treatment Plant in 1981. This showed that substantial savings in fuel consumption could be achieved with an appropriate process control strategy. The fundamentals of this strategy are to (1) keep the burn zone low in the furnace, about two hearths above the bottom; (2) utilize shaft cooling exit air to the maximum degree; and (3) minimize the excess air amount and off-gas temperature as much as possible while still achieving desirable air quality standards. The first and second goals provide the maximum amount of area above the burning sludge for the drying process and use heat generated by the sludge combustibles instead of purchased fuel. The third goal prevents heat waste by minimizing mass flow and heat content in the off-gas. These main goals, together with supporting instructions, were also the basis of revisions implemented in sludge incinerators at Nashville, TN; Buffalo, NY; and Hartford, CT, all of which are subautogenous feed situations. The following list is a blend of general operating procedures utilized at Indianapolis and Nashville:

1. Maintain steady feed rate.

2. Maintain top hearth draft at 0.51 to 2.03 mm (0.02-0.08 in) of water negative.

3. Maintain oxygen level at 4-5 percent at full rated loading, somewhat higher at partial load, and a maximum of 8 percent at 55 percent of rating. These are for readings in-situ on hot gases containing vaporized and combustion moisture; after scrubbing and cooling, the values would be 2-3 percent higher because most of the moisture would be removed.

4. Control burn zone on hearth 6 (of 8, Indianapolis) or 7 (of 10, Nashville). This is managed mainly by burner firing rate control.

5. Minimize or eliminate any use of burners on hearths above the burn zone. If a choice is made, use lowest burners and only to control the initiation point of combustion.

6. Keep center shaft speed at a low, steady rate—100 seconds per revolution or longer. Do not attempt to manage burning zone by varying the shaft speed.

7. Use only shaft cooling return air for sludge combustion.

8. Limit maximum hearth temperature to 843° - 899°C (1,550° - 1,650°F) to prevent formation of clinkers.

9. Allow top hearth temperature to be what it will; do not use higher hearth burners to reach an arbitrary standard, although occasional use for smoke abatement during upset conditions is allowable.

As an added benefit, this strategy is reported to provide improved performance of scrubbing equipment and better compliance with emission standards.This result is probably due to the lowered air velocities attributable to less excess air and lower off-gas temperatures, which cause less entrainment of fly ash.

Hartford, CT, Case History

The Hartford Water Pollution Control Plant provides primary and secondary wastewater treatment for more than $170 \times 10^3 m^3$ (45 Mgal) of wastewater per day and generates in excess of 180 Mg (200 tons) of sludge cake per day. The sludge handling facility was originally designed in 1968 with four dissolved air flotation thickeners, five vacuum filters, and three multiple-hearth incinerators. In 1978, before the conversion to belt filter presses described previously in this chapter, the vacuum filters averaged 13.8 percent cake solids. Production required continuous operation of three of the five vacuum filters, with two of the three incinerators operating around the clock. The plant operation experienced the typical production and maintenance problems associated with handling an extremely wet sludge cake. In addition, the Hartford plant started to receive sludge from satellite plants in East Hartford and Rocky Hill. The incinerator operations were plagued with the operating problems of handling very wet sludge cake and consuming large amounts of fuel. A Hartford incinerator is shown schematically in Figure II-5. It is equipped for either gas or oil operation and rated at 11.3 wet Mg (12.5 wet tons) per hour. No common operating procedure was used by the incinerator operators. Each operator had certain specific practices and techniques for maintaining

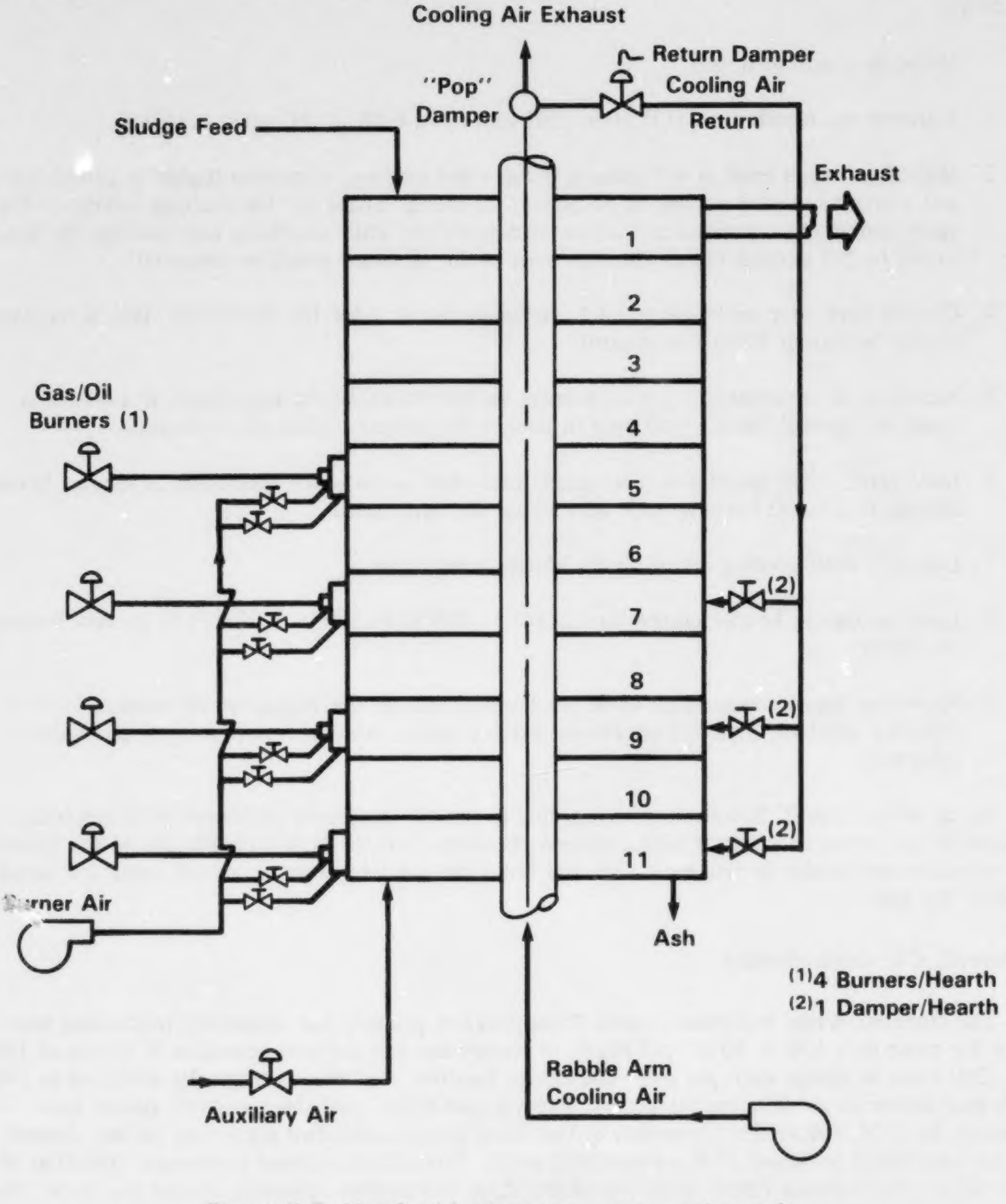

Cooling Air Exhaust
Return Damper
Cooling Air
Return
"Pop" Damper
Sludge Feed
Exhaust
1
2
3
4
5
6
7
8
9
10
11
Gas/Oil Burners (1)
(2)
(2)
(2)
Burner Air
Ash
(1)4 Burners/Hearth
(2)1 Damper/Hearth
Rabble Arm Cooling Air
Auxiliary Air

Figure II-5. Hartford incinerator system schematic.

temperatures on various hearth levels and for managing incinerator airflow. The operators' preoccupation with just burning the very wet sludge cake resulted in many inefficient operating practices.

Fuel Reduction Program. Reductions in fuel consumption for sludge cake incineration were accomplished in two ways. The first was to substitute belt filter presses in place of coil-type vacuum filters, and the second was to modify the MHF operating methods and upgrade their control system. The second change involved the acceptance and implementation of advice presented by a specialized consulting firm. Based on a careful study of equipment and operating practices, a new operating mode was undertaken, and the collection and analysis of data was improved. The result was more uniform procedure among the various shift operators and adherence to a greatly revised format of operating variable control. Overall, this reduced fuel consumption by 83 percent, which in dollar terms amounted to a savings of over $1,300,000 for 1982 compared to operation in 1978 and before the changes.

To provide an accurate baseline for comparing the fuel reduction achieved by converting to belt filter presses and improving incinerator operation, a statistical analysis was made of key performance data, including temperature and oxygen content of the off-gas, fuel consumption, and air usage for past operations and each of the years during which changes were made. In addition, the correlation of specific fuel consumption (SFC) measured in liters of oil consumed per dry kilogram (gal/ton) with the absolute sludge cake moisture to volatile ratio by weight (M/V) was computed to provide a more comprehensive measure of change for comparison:

$$M/V \quad \frac{1 - s}{s \times v}$$

where

s = fraction solids in cake
v = fraction volatiles in cake solids

The M/V ratio is a site-specific parameter that is useful at a given plant for process control, but is limited for interplant comparison to those having similar volatile heat values and running at comparable excess air ratios and breech temperatures. The average specific fuel consumption for the Hartford incinerator operations in 1978 was 0.52 liters of oil per dry kilogram (125 gal/ton). The sludge cake solids averaged 13.8 percent and the volatiles averaged 77.1 percent. The sludge cake M/V ratio, which is directly related to and principally determines the specific fuel consumption demand, averaged 8.6; this is relatively high. For example, if evaporative effectiveness is 4,700 kJ/kg (2,000 Btu/lb) of water and sludge volatiles have 23,000 kJ/kg (10,000 Btu/lb) of heat value, both expressed in gross heating value, cake having an M/V ratio of 5.0 would be autogenous. Any higher M/V in this plant would require fuel. At 8.6, the cake would require 3.6 times 4,700 kJ/kg (2,000 Btu/lb) or additional 17,000 kJ/kg (7,200 Btu/lb) of volatile solids to reach balance at the exit gas temperature and oxygen content because of the large amount of moisture in the sludge cake.

Operational Testing and Analysis. An operational analysis was made of the Hartford incinerator operations and included measurements of airflow; analysis of exhaust gas; and assessments of key instrumentation and controls, existing operator-specific practices, feed rate management, airflow management, burner use profiles, hearth temperature profiles, and combustion zone location and control. A demonstrated and proven kinetic incinerator analytical model was also used to determine the optimum loading rate and plant operating mode that would result in the minimum possible fuel consumption. Preliminary investigation of operator practices found that no uniform operating procedure was used. There were several operating practices and lack of controls that were contributing to excessive fuel consumption such as:

- Combustion occurring too high in the incinerator;
- High exhaust gas temperatures;
- High draft settings and too much auxiliary air;
- Misuse of heated rabble arm cooling air;
- Improper burner use choices;
- Improper techniques for controlling combustion zone location; and
- Lack of remote operator controls for airflow dampers and burners.

A preliminary analysis indicated that optimum airflow management could result in a potential fuel reduction of 70 percent when burning sludge cake with an M/V ratio of 5.0 at an incinerator loading of 6 tons/hr. Two examples of M/V at 5.0 would be 22 percent solids cake at 71 percent volatile and 25 percent solids at 60 percent volatile. The two main parameters of furnace off-gas (breech temperature and oxygen in the off-gas) must be kept as low as possible without violating air emission limits.

The kinetic analysis for these conditions predicted that the potential fuel consumption for the Hartford operation with such a dry cake was *zero*. This analytical result agreed with the empirically based preliminary estimate drawn from airflow management, since an additional 30 percent of fuel savings could be reasonably expected from improved combustion zone location control, optimum burner use, improved load rate management, and the synergistic effect of these operating mode techniques on fuel consumption. Based on these results and those from similar programs in Indianapolis, Buffalo, and Nashville, periods of autogenous combustion were expected with the new operating mode. Autogenous combustion was achieved several times during the operational trial and demonstration test for as long as 8 hours. During the period of routine use of the new operating mode, there were many days in which no fuel was used over a 24-hour period. Based on the operational trial tests and analyses, a new operating mode with specific instructions and operating settings was developed. The new operating mode was then demonstrated in full-plant operation for a 2-week performance demonstration test period. On-the-job operator training in the use of the new mode was also accomplished at the same time, since this is the only way to ensure continued good operation. After completion of the successful performance test, the operating mode was further refined for routine operational use.

The new operating mode was characterized by the following general operating guidelines:

- Maximize the use of the heated rabble arm cooling air return;
- Use the least possible draft (i.e., just slightly negative) to minimize air leakage;
- Combust on the third lowest hearth to maximize drying area;
- Replace cold auxiliary air supply with heated cooling air return;
- Minimize excess air by observing and minimizing oxygen in flue gas;

- Use lower hearth burners to maximize drying temperature;
- Eliminate airflow to top hearth burners;
- Control combustion zone location with burner use profile;
- Slow center shaft speed to improve sludge drying;
- Discontinue use of hearth No. 5 burners; and
- Use the following operating parameters in breech:

Oxygen	4-5 percent in the raw off-gas, which equates to about 7.5 percent on a moisture-free basis after scrubbing
Draft	0.05-0.20 cm (0.02-0.08-in) w.c. (negative)
Temperature	370° - 425°C (700° - 800°F)

The specific operating instructions that constituted the new operating mode were given to the incinerator operators and included procedures for sludge load management, incinerator operation control, specific settings for normal operations, combustion zone location control, standby and startup operations, and techniques to control sludge cake "burnouts." The most effective incineration/dewatering configuration was for two BFPs to feed each operating incinerator. The optimum incinerator loading rate was found to be 6.6 Mg (6 wet tons) per hour per incinerator, approximately half the design basis, based on analysis and trial tests of load rates between 5.0 and 7.7 wet Mg (4.5 and 7 wet tons). The 6.6-Mg (6-ton) per hour load rate was the minimum rate needed to keep up with the overall plant production rate and still minimize fuel consumption, considering that the average sludge cake M/V ratio was 4.5. (A 4.5 M/V would mean, for example, 22 percent solids and 79 percent volatile or 25 percent solids and 67 percent volatile.) The improved operating mode also enabled a further reduction in the M/V ratio because the new mode allowed the dewatering presses to be slowed down, resulting in drier cake.

Fuel Reduction Results. The new incinerator operating mode was placed into routine operation immediately following the 2-week performance test conducted in January 1982. Operational data for 1982 were analyzed to measure and compare the fuel reduction achieved. Shown in Figure II-6 is the computed least squares correlation of the average specific fuel consumption vs the sludge cake M/V ratio for the baseline period 1978-81 and for 1982. The improved thermal operating efficiency achieved is reflected in the change of the slope of the relationship. This result was quite similar to what occurred in Indianapolis, Nashville, and Buffalo when these plants implemented similar operating techniques. Figure II-7 shows the average specific fuel consumption for the Hartford operations from 1978 through 1982. The average specific fuel consumption for 1982 was 0.091/dry kg (21.1 gal/dry ton) as compared to 0.18 (43.5) for 1981, approximately a 51.5 percent reduction. With this improvement, the total fuel reduction achieved by Hartford between 1978 and 1982 amounted to 0.431/dry kg (104 gal/dry ton), or 83 percent, which at the 1982 production level represented a savings of 4,074.568 m^3 (1,076,504 gal) of No. 2 fuel oil as compared to 1978.

In addition to reducing direct fuel consumption, the new operating mode provided increased operating flexibility with the equipment because the incinerators could now be operated efficiently at load rates 50-60 percent of capacity, which was not possible before without paying a tremendous penalty in excess fuel consumption. Incinerator operation is also now characterized by cooler max-

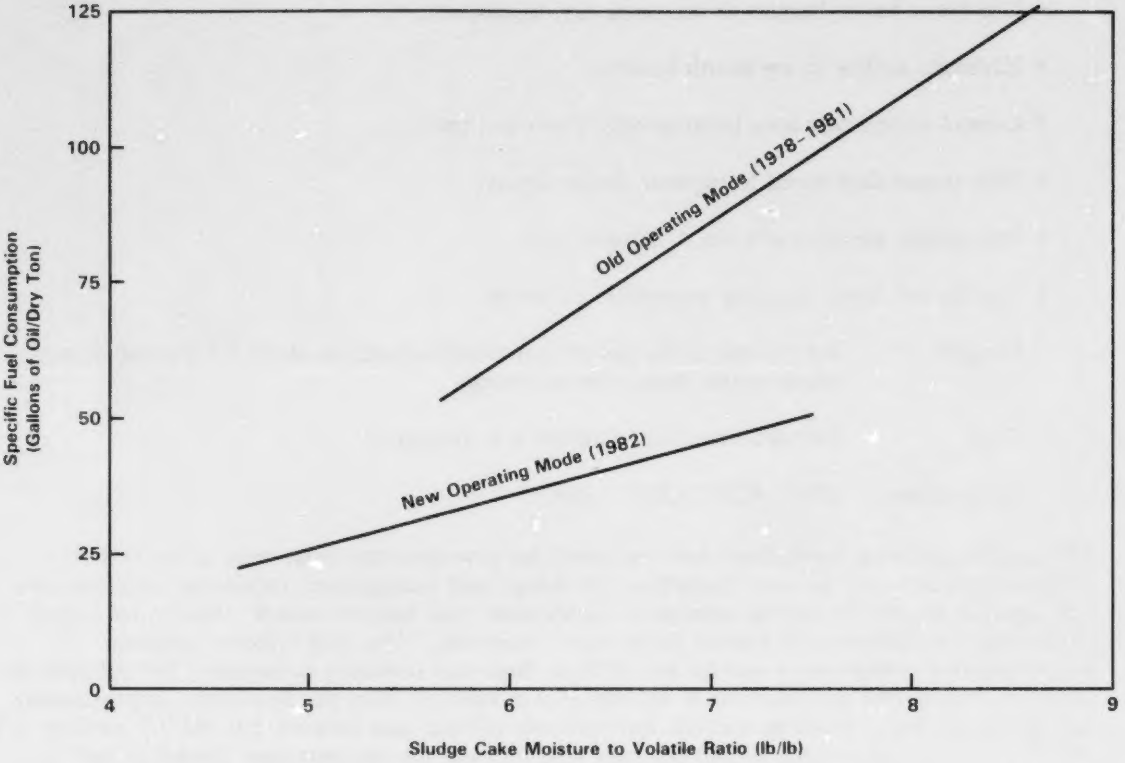


Figure II-6. Specific fuel consumption vs sludge cake M/V ratio before and after incinerator operating mode change at the Hartford plant.

imum operating temperatures, more steady state control, less particulate emissions, and reduced maintenance on internal incinerator parts.

Cost Savings. The nominal cost savings from reducing incinerator fuel consumption on an annual basis were estimated from the change in the specific fuel consumption from 0.52 to 0.091/dry kg (125 to 21 gal) of oil/dry ton. Based on 1982 production of 9,388.4 dry Mg (10,351 dry tons), the savings would be over $1,076,000 per year using an estimated price of $0.26 per liter ($1 per gallon) for No. 2 fuel oil. The total estimated annual operating cost savings from converting to belt filter presses and the new incinerator operating mode are over $1,300,000 per year.

AUTOGENOUS COMBUSTION

In Japan

In Japan, there are at least two plants utilizing the principle of autogenous combustion with MHFs. For dewatering, a belt filter press is used at the Yotsuya Treatment Plant in Takaoka City, while a recessed plate pressure filter is used at the Hojin Treatment Plant in Nagoya City. Autogenous combustion at these plants was made possible not only by such factors as optimum dewatering and incineration processes, but also by the improvements that resulted from the challenge to operators and other personnel to achieve autogenous combustion.

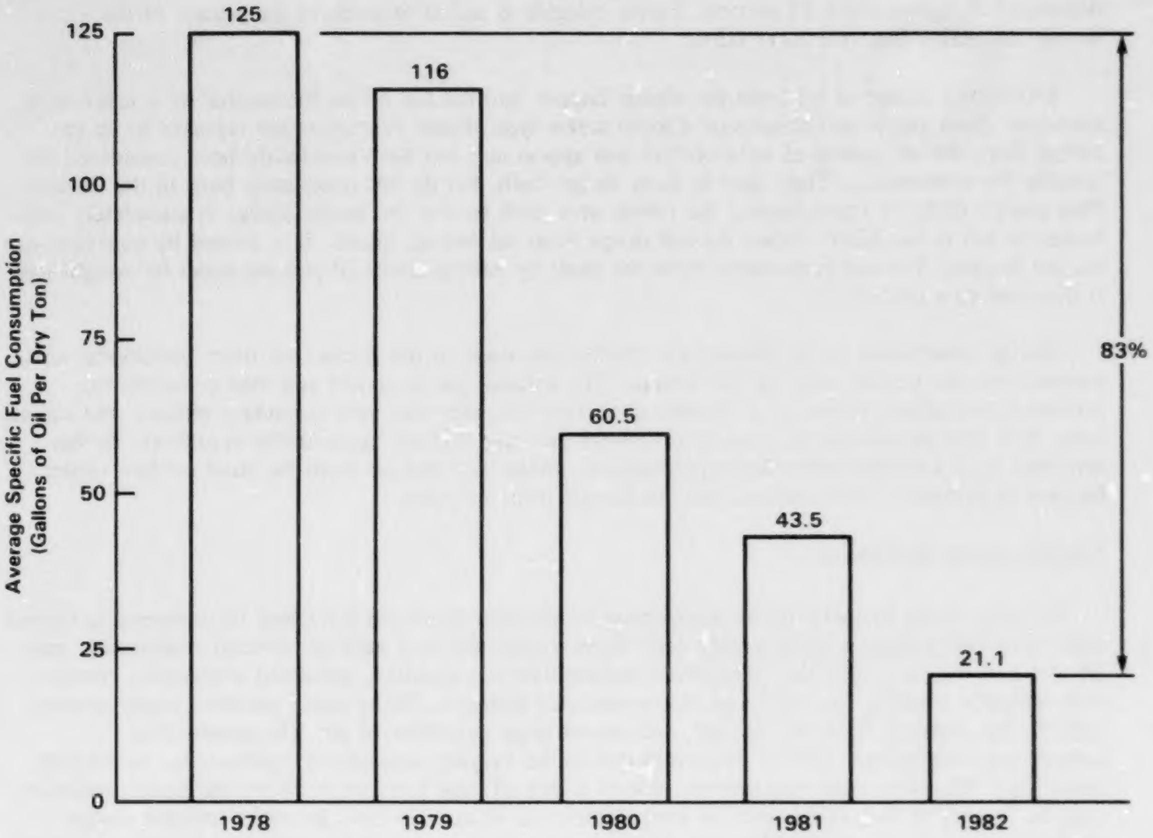


Figure II-7. Average specific fuel consumption for the Hartford operations, 1981-82.

Yotsuya Treatment Plant Case History. The six-hearth incinerator at this treatment plant started operation in July 1979 and has since operated in an autogenous combustion mode. Supplementary fuel is only needed to heat the furnace at the start of combustion. Incinerating capacity is 30 wet metric tons per day. Feed is dewatered on high-pressure BFPs. In 1981, 19,521 liters (5,157 gal) of heavy oil were used for 8,122 Mg (8,934 tons) of dewatered sludge at 30 percent solids content. This showed that, on the average, only about 8 liters (2 gal) of heavy oil were used to incinerate one metric ton (1.1 tons) of dewatered sludge solids. This incinerator is clearly one of the most energy-conserving in Japan, since the consumption of supplementary fuel (heavy oil) by incinerators is commonly 170 liters (45 gal) per ton of solid matter for a MHF. The savings in heavy oil achieved by autogenous combustion represent about 7 percent of the total operation and maintenance cost for the treatment plant. Currently, the incinerator operates on a weekly cycle (i.e., it starts on Monday and stops on Sunday). Switching to long-term continuous operation is technically possible, and, if this is done, the number of heatup times will be reduced and costs further lowered.

Discussing the operation in greater detail, thickened sludge at a concentration of about 4 percent solids is dewatered by high-pressure BFPs after being conditioned with polymer at 0.5-0.8 parts by weight per hundred (pph) and ferric chloride at 5-7 pph dosage rates. The solids content of the dewatered sludge is about 38 percent. Ferric chloride is added to improve the release of the dewatered sludge from the filter fabric.

Dewatered sludge is fed from the sludge hopper into the top of the incinerator by a screw-type conveyor. Both are closed structures. Closed screw-type sludge conveyors are reported to be excellent from the standpoint of odor control and appearance but have previously been considered unsuitable for incinerators. They tend to form sludge balls that do not completely burn in the furnace. This plant's designer reconstructed the rabble arm teeth so that the lumpy sludge is completely combusted to ash in the MHF. When the ash drops from the bottom hearth, it is moved by conveyor to the ash hopper. The ash is removed from the plant by adding about 20 percent water by weight and is disposed to a landfill.

Sludge combustion air is induced into the bottom stage of the furnace by draft. Additional air is induced into the middle stage of the furnace. The exhaust gas is cooled and thus dehumidified, scrubbed, and alkali-washed in a cyclone spray-type scrubber that uses secondary effluent and caustic soda. It is then deodorized by passing it through acid and sodium hypochlorite scrubbers, further scrubbed by a wet-type electrostatic precipitator, mixed with hot air from the shaft cooling of the furnace to prevent a steam plume, and discharged from the stack.

Problems and Solutions

In early trials, incineration by autogenous combustion displayed a number of problems compared with incineration using supplementary fuel. Even though the heat balance between combustible matter and moisture indicated that autogenous combustion was possible, stabilized autogenous combustion operation could not be achieved in conventional furnaces. Three major problem areas included unstable combustion, unburned sludge, and use of large quantities of air. The combustion temperature and location shifted frequently due to the varying amounts of combustibles in the feed. Since the combustion zone was narrow, due to a lack of heat from the burners, the sludge retention time on the hearth was short, and the temperature was frequently low; therefore unburnt sludge resulted. High air use resulted because the combustion temperature was controlled by the amount of cooling air; as the air ratio increased, heat loss to the exhaust gas increased and thermal efficiency deteriorated.

Stabilized autogenous combustion operation resulted from the introduction of the procedures discussed here. The volume of primary air flowing into the bottom stage of the furnace can be automatically controlled, taking advantage of the draft effect that changes according to load change in the furnace and the change of sludge character. This widens the combustion zone and prevents the lowering of the surface temperature and the discharge of unburned matter in conjunction with a change in the combustion load. The hearth with the greatest temperature in the combustion zone can be detected with a sensor and the volume of secondary air directly induced into the combustion zone can be manipulated so that the temperature on this hottest hearth is held between 700° and 900°C (1,300° and 1,650°F). In times of low-load operation, the operation can be governed by moving the combustion hearth up higher in the furnace. Thus, heat radiated from the furnace walls and the center shaft can be reduced and the lowering of the thermal efficiency prevented. These control measures prevent unstable combustion, high air ratios, and discharge of unburnt sludge; they also minimize clinker and slag formations.

Performance Test of MHFs at Yotsuya. An experimental program was undertaken by the Japanese to investigate the conditions required for autogenous combustion in a MHF. This was done by changing both the amount and the solids content of dewatered sludge put into a furnace. The sludge employed for the study had a volatile solids concentration of 70 percent, and its high heat value was 5,800 kcal/kg (10,453 Btu/lb) VS. The incinerator was designed to handle 30 metric tons/day (33 tons) of dewatered sludge with a water content of 70 percent and a volatile solids content of 70 percent.

In the study, stabilized autogenous combustion with an input load range of 9.5-40.6 metric tons/day (10.5-44.7 tons) was possible if the net heating value (NHV) of the input dewatered sludge was 400 kcal/kg (720 Btu/lb) cake or more. This range was 32-135 percent of the design value; thus, it was clearly possible to handle a very wide range of loads. In this test program the NHV of the dewatered sludge was only 350-370 kcal/kg (631-667 Btu/lb) cake. Maintaining the condition of autogenous combustion for more than 6 hours was possible in some cases but impossible in others. This seems to show that if the sludge has a low calorific value of under 350-370 kcal/kg (631-667 Btu/lb) cake, autogenous combustion in the furnace is not practical (NHV takes into account the heat sink effects of sludge moisture, combustion products, and excess air, all raised to furnace exit temperature).

The properties of exhaust gas at the furnace outlet were found to be as follows:

NO_x concentration	100-260 ppm, related to 12 percent oxygen concentration
HCN concentration	ND-66 ppm, related to 12 percent oxygen concentration
Dust	0.2-1.4 g/Nm^3
Odor concentration	4,100-7,300 in autogenous combustion; 17,000 in combustion using supplementary fuel

It was found that odor concentration was lower in autogenous combustion than in combustion with supplementary fuel. When the degree of conversion into NO_x and SO_x was calculated with respect to N and S quantities in dewatered sludge put into the furnace, on the assumption that 10 ppm of thermal NO_x will be created at 800° - 850°C, the conversion from N into NO_x was 2.0-4.7 percent, and the conversion from S into SO_x was 84-120 percent. These values generally agreed with NO_x and SO_x production in existing furnaces. The unburned portion of incinerated ashes was nil to 0.67 percent; thus the extent of sludge combustion was very satisfactory.

Hojin Treatment Plant Case History. At the time of its planning, the incinerator at the Hojin Treatment Plant in Nagoya City was believed capable of autogenous combustion. However, when it began operation in April 1979, it could not be operated in the autogenous mode. As the control system for incineration was improved, however, oil consumption went from about 10 liters (2.6 gal) per metric ton of dewatered sludge to less than 3 liters (0.8 gal), including that required for startup or maintenance of temperature when not burning.

Thickened sludge with a solids concentration of 3-4.5 percent is dewatered by a horizontal recessed plate pressure filter after dosing with ferric chloride at about 8 pounds per hundred pounds (pph) dry sludge solids and slaked lime at 25-30 pph. The solids content of the dewatered sludge is 32-45 percent and the filtration yield is 3-6 kg/m^2/hr of dewatered sludge solids. Because of its relatively low water content, the sludge is mixed by a pug mill and fed to the incinerator. The slablike sludge cake is crushed in the mill to permit easy handling on a conveyor. This improves both drying and combustion in the furnace. The incinerator has 10 hearths, but the first does not function as a drying hearth. It is provided for potential future use as an afterburning chamber for exhaust gas deodorization. Nine hearths are used to carry out the incineration process, and the fifth and sixth are the usual combustion hearths. At present, exhaust gas is treated by water scrubbing, alkali scrubbing, and electrostatic precipitation.

Average incinerator operation conditions prior to upgrading were: furnace outlet temperature, 330°C (625°F); miscellaneous heat loss, 8.4 percent of the total heat input; sludge feed rate, 4.0 metric tons/hr (4.4 tons) of sludge solids concentration of 20-40 percent; and a calorific value within the range of 2,500-4,000 kcal/kg (4,505-7,209 Btu/lb) dry sludge. Since dewatered sludge at the Hojin Treatment Plant typically has a calorific value of about 2,600 kcal/kg (4,700 Btu/lb) dry solids, the limiting dewatered sludge solids content in autogenous combustion was 34 percent, and the limiting NHV was 450 kcal/wet kg solids (810 Btu/lb).

Upgrading of operations basically included the development of a combustion control strategy and refurbishing to permit automatic control. The furnace temperature was formerly controlled using the temperature in the third hearth as a reference. The fifth hearth, which was the combustion hearth, was made the index. Temperature control in the sixth and seventh hearths also was made possible because it was assumed that the combustion hearth could actually be the sixth or seventh hearth, depending on the amount and properties of the dewatered sludge. The selection of the control hearth is made manually. So that the gas temperature can be measured without being affected by flames, the length of projection of a thermocouple into the hearth was reduced. Two thermocouples were installed in the fifth hearth, with a view towards higher measurement accuracy and ready detection of the failure of either. Air for autogenous combustion was formerly supplied from the burner blower. This was changed to a method that supplied combustion air in proportion to sludge input rate, by positioning an air damper on a duct that branched from the central shaft cooling fan. The furnace temperature can now be controlled by adjusting the volume of air handled by the exhaust gas fan rather than by supplying tempering air from the burner blower. Instruments were added and their control capability was improved. As a result, the variation in furnace temperatures has decreased, and combustion has stabilized.

Autogenous Combustion Control System

Incineration is stabilized by controlling the air volume and furnace pressure. Three temperature control levels, 800°, 850°, and 900°C (1,470°, 1,560°, 1,650°F), are available as temperature setpoints and are measured in the fifth hearth (or in the sixth or seventh hearths, if this is where combustion occurs). The process control variables are air volume and furnace draft. Control is executed by a closed temperature feedback loop: temperature control setpoint—process variable control—temperature variation— process variable control. In the temperature range of 800° - 900°C (1,470° - 1,650°F), which is the most desirable operating range, combustion air volume is controlled in proportion to sludge input. Draft in the furnace for 800° - 850°C (1,470° - 1,560°F) is fixed at −30 mmAq (negative pressure of 30 millimeters measured by a water column draft gauge). When the temperature exceeds 850°C (1,470°F), the furnace draft is gradually increased and cooling is effected. If 900°C (1,650°F) is exceeded several minutes later, the proportional control of combustion air is lifted and air for combustion plus cooling is supplied. If the temperature at the fifth stage reaches 1,000°C (1,830°F), cooling air is increased by operating the burner blower. If 1,050°C (1,920°F) is reached, sludge feed is stopped. In cases of temperatures below 800°C (1,470°F), a temperature rise is generated by reducing draft to −10 mmAq, which reduces the excess air and quenching effect. If the temperature is still below 800°C (1,470°F) several minutes later, combustion air is manually reduced after lifting combustion air control in proportion to sludge input.

Properties of Exhaust Gas

The results of exhaust gas analysis at the outlet of the electrostatic precipitator are characterized by a small emission of NO_x and SO_x. NO_x emission was 0.2-0.4 g/kg of cake feed. SO_x emission was often below the detection limit value. At other sludge treatment plants in the city, where sludge is dewatered by vacuum filters and incinerated by MHFs with auxiliary fuel, the NO_x is typically

0.6-0.8 g/kg of cake feed. As in the case of SO_x, this seems to be due mainly to the fact that heavy oil is not the main fuel.

SUPERAUTOGENOUS (HIGH-CALORIFIC) COMBUSTION

Burning sludge cake with a high net positive heat value requires special consideration. In the past decade, a number of municipal sludge incinerators were built to combust sludge cake that has more heat value than the water in the cake requires for evaporation and elevation of flue gas temperature. These cakes are produced from either thermally conditioned sludge or raw primary sludge, the latter perhaps containing grease and oil or admixed scum. The increasing adoption of BFPs and recessed plate filter presses that can more effectively dewater sludges has generated concern about burning this type of dewatered sludge cake in furnaces of the multiple-hearth type, which were designed for cakes that require significant drying before combustion can begin. FBFs do not raise these concerns, but have other factors that limit their acceptance.

These feeds are termed "hot" in the sludge processing industry. Other terms that apply are high calorific and superautogenous, or simply autogenous meaning that the cake maintains itself in combustion without the need for auxiliary heat sources. Sometimes burning these sludges produces a high flue gas temperature at the furnace breech, which causes excess air emissions or higher than desirable flue gas temperatures at the furnace outlet. Various approaches have been proposed by combustion specialists in the sludge incineration field to manage the burning process within acceptable limits, to prevent damage to the furnace, and to prevent episodes of massive combustion on several hearths at once. All of these problems have in fact plagued some of the early projects. Perhaps the first instance of serious damage to a furnace was the loss of the top two hearths at Kalamazoo, MI, in 1974. This was caused by premature burning of the thermally conditioned sludge in the topmost part of the furnace. The system had been put into service a few years earlier, and the design was only suited for handling raw primary sludge cake; it was not appropriate for "hot" feed. One of the first methods of control, based on the presumption that the volatiles needed more room for combustion, was to feed to the second or even a lower hearth. This was done by providing an enlarged drophole immediately below the feed entry chute or, in a few cases, by mounting a screw conveyor in the sidewall of the furnace to inject cake laterally at the desired hearth. The screw conveyor approach, as applied in 1972 at Muskogee, OK, to handle thermally conditioned sludge filter cake, suffered from burn-back difficulty and has seldom been used. Another project where a great deal of difficulty occurred was in the MHF at Atlantic County, NJ. The sludge, after heat treatment, had an unusually high heat value, and it was necessary to modify the furnace internally and provide additional air for quenching.

A well-known furnace manufacturer has modified the design of the air input system to overcome much of the past difficulty experienced with hot sludge. This design was applied as a retrofit at Lansing, MI, and in a new furnace started up in late 1983 in Hawaii. Neither of these cases represents a complete and perfect adoption of the design principles, but both have shown substantially better performance than could be expected from previous furnace systems. A case history of the retrofit at Lansing follows. It illustrates the performance of an incinerator that combusts high-calorific sludge cakes.

Lansing, MI, Case History

The original incinerator design at Lansing, MI, was for burning a nonautogenous sludge cake; however, it could not satisfactorily operate within allowable particulate air emission standards while burning the superautogenous sludge that was produced with the adoption of a thermal sludge conditioning process. In 1978, the sludge was thermally conditioned and dewatered by a rotary vacuum drum filter to a 50-60 percent solids concentration. In addition, the heating value of dry cake was 7,200-7,800 kcal/kg (13,000-14,000 Btu/lb) compared to a 4,200 kcal/kg (7,500 Btu/lb) design value normally experienced and used for sludge furnace design purposes in the United States.

Modifications to the furnace and its control system were completed in 1982 and corrected the deficiencies. The main feature of this new design, known as Cyclo-Hearth® , is a distributed sludge combustion air supply that allows air to be routed where needed for temperature management and prevents overheating when burning a superautogenous cake. This air management system consists of two elements: (1) individual supplies to each hearth that are readily modulated with accuracy by automatic or operator intervention and (2) a swirling effect induced by air jets that operate when burners are shut off to simulate the burner gas dynamics and thus promote the equalization of temperatures laterally in a hearth. The Cyclo-Hearth MHF consists of a number of discrete furnaces (or hearths) acting together in series rather than a single massive operation. The basic design of the Cyclo-Hearth MHF (see Figure II-8) is implemented through the following provisions. Temperature

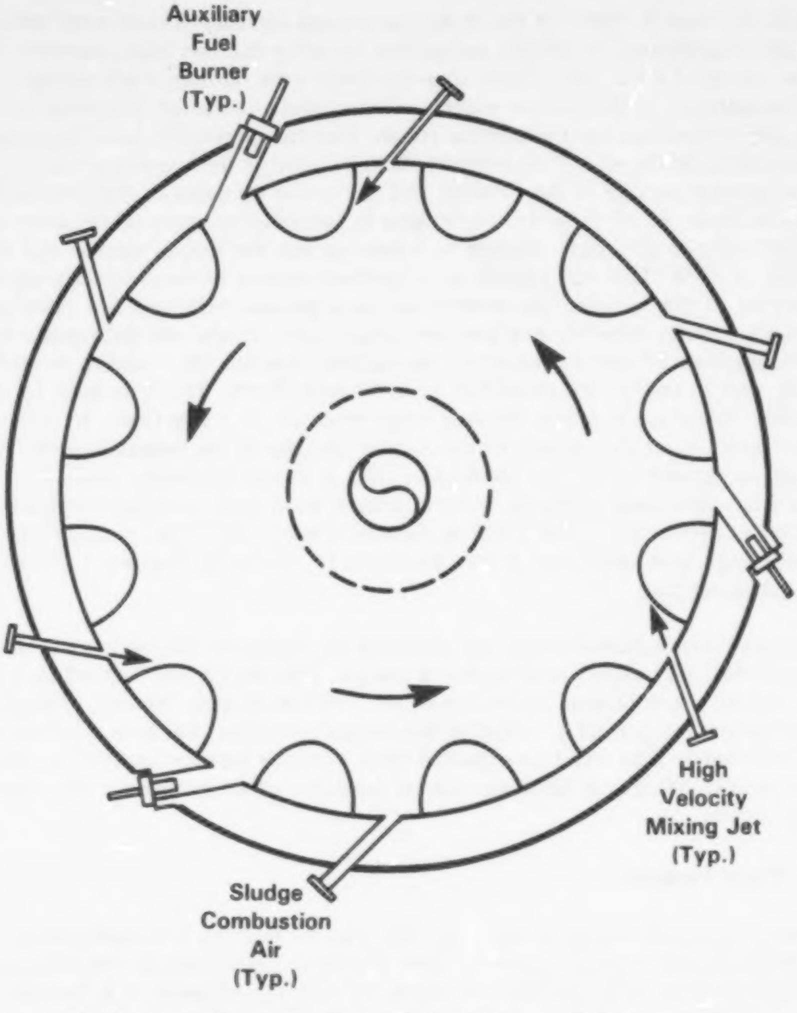

Auxiliary Fuel Burner (Typ.)
High Velocity Mixing Jet (Typ.)
Sludge Combustion Air (Typ.)

Figure II-8. Schematic of the Cyclo-Hearth® multiple-hearth furnace.

is controlled on each hearth by modulating either the burner firing rate or the sludge combustion air rate, but not both simultaneously. For instance, if a hearth is on burner control with the burners firing at a low rate and the hearth temperature rises above the set point, combustion control logic will switch the hearth to combustion air control. Control logic will also switch in the opposite direction as conditions warrant. Exhaust gas oxygen content (excess air rate) is maintained at the set point value by allowing the oxygen analyzer to override the temperature control signal to the bottom hearth. This will allow the bottom hearth sludge combustion air valve to modulate and admit more air as required. High-velocity mixing jets impart turbulence to unfired hearths by directing a stream of air tangent to a circle, dividing the hearth area approximately in half. Operation of the jets is only required on unfired hearths and on fired hearths when an autogenous sludge is being incinerated. By promoting turbulence, complete combustion, and uniform hearth temperature, these mixing jets allow greater response to furnace conditions and eliminate control circuit instability caused by delayed combustion. Furnace draft is controlled by varying the position of the adjustable throat in the Venturi scrubber, to allow better particulate emission control with no increase in electrical power consumption.

Modification work at Lansing, MI, was restricted to the furnace, sludge combustion air fan, air distribution system, and sludge feed point. The waste heat boiler, scrubbing system, and induced draft (ID) fan remained unchanged. The modified furnace is shown schematically in Figure II-9. Three sludge combustion air ports were added to the first through third hearths, thus enabling this air to be added wherever needed in the furnace. A damper was placed in each 25-cm (10-inch) sludge combustion air line to the furnace. These dampers can be controlled by the temperature controller on each hearth or manually by the operator. In the automatic control mode, each hearth temperature would be maintained at its set point by the flow of sludge combustion air to that hearth. To provide adequate sludge combustion air, a larger ID fan was needed.

Three mixing jets were added to the first through fifth hearths. The purpose of these jets is to provide gas-phase turbulence in these hearths when no burners are being used. The mixing jet air is taken from the burner combustion air lines. Mixing jet air is controlled manually with valves located in each line to the furnace. The operators determine when and how much mixing jet air is to be added to the furnace based on the temperature profile of the furnace and visual observation of the hearth conditions. No modifications were needed in the burner combustion air fan to accommodate this change, since mixing jet and burner combustion air are not needed simultaneously. The sludge feed point was moved to a lower hearth, allowing more gas residence time in the top hearths to achieve adequate combustion of the volatiles. The sludge feed can now be varied between hearths three or four as determined by the operator. The rabble arms were removed from hearths one and two, and refractory feed chutes were installed to bring the feed cake from the top of the furnace to the new feed hearths. A single burner was added to hearth one in case it was necessary to have an ignition source to ensure combustion of volatiles remaining at that point.

Modification Results. Operation of the modified system began in March 1982, on a 5 day/week, 24 hr/day schedule. The system operated at a wet feed rate of 3.6-4.5 Mg/hr (4-5 tons/hr), with roughly a 50 percent total solids content cake, and was able to meet air emission requirements. With the feed split between hearths three and four, there is adequate gas residence time in hearths one and two to allow complete combustion of the gaseous volatile material. In addition, the temperature of these "afterburner" hearths can be controlled by the supplemental air injection. In a similar fashion, the feed hearth temperatures are also controlled by the addition of sludge combustion air. The operators can control temperatures on these feed hearths at 540° - 650°C (1,000° - 1,200°F) even though the sludge is burning at these conditions. Maintenance of the desired temperature profile in the furnace has reduced clinker formation to a minor operating problem.

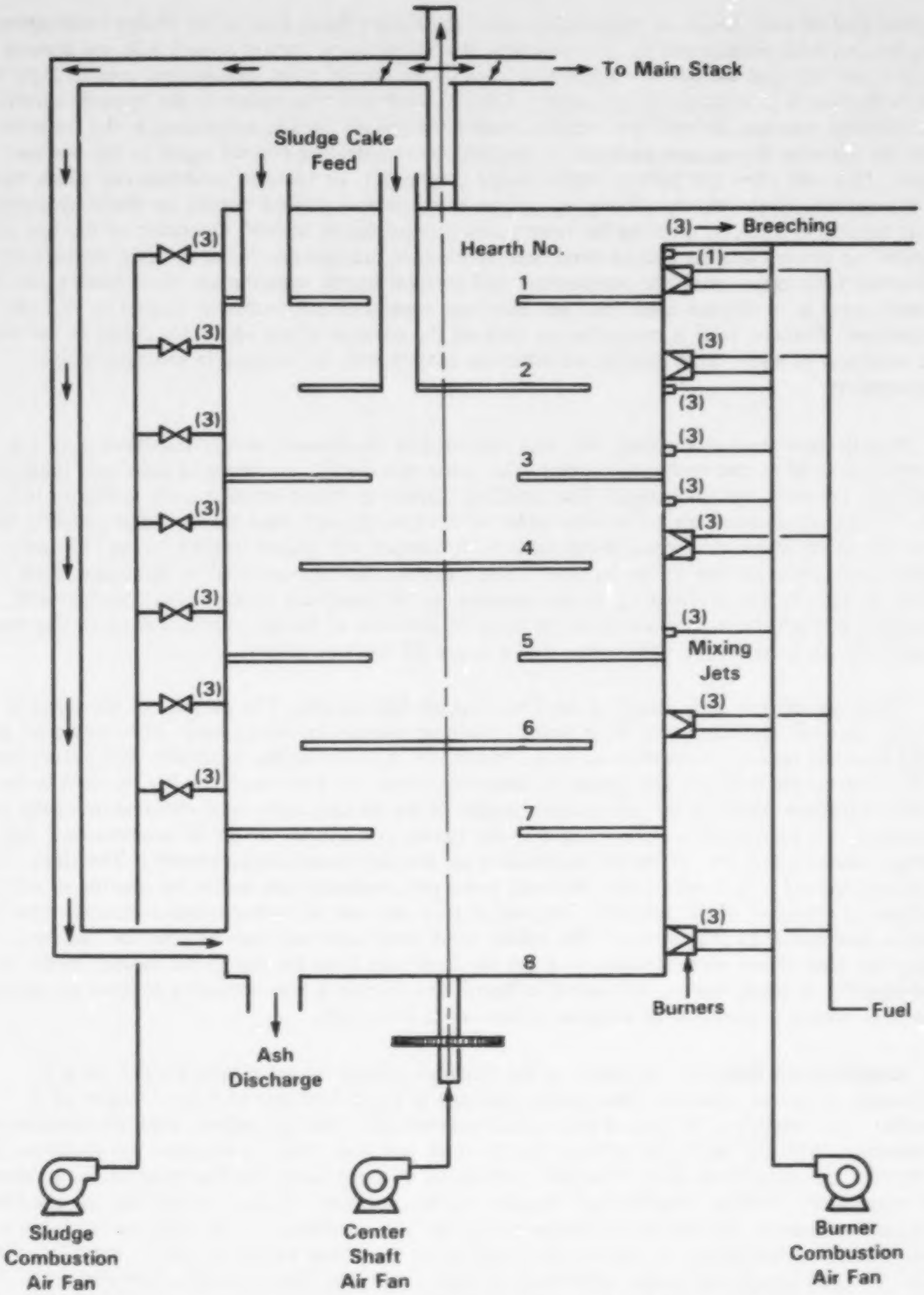

To Main Stack
Sludge Cake Feed
(3) Breeching
Hearth No.
(1)
(3)
1
2
3
4
5
6
7
8
Mixing Jets
Burners
Fuel
Ash Discharge
Sludge Combustion Air Fan
Center Shaft Air Fan
Burner Combustion Air Fan

Figure II-9. Modified Cyclo-Hearth® furnace configuration.

The sludge feed distribution between hearths three and four is determined by the sludge cake solids content. Should the temperature of hearth three increase in spite of large combustion air rates to that hearth, indicating a hotter sludge, the operator diverts more sludge to hearth four, thus maintaining the proper temperature profile. Conversely, when little combustion air is directed to hearth three and that hearth temperature begins to drop, the sludge feed rate to that hearth is increased. The modified furnace is also capable of handling fluctuations in feed quite successfully. If the addition of an autogenous sludge is stopped for a brief period of time (e.g., 10-15 minutes), the operator simply reduces the amount of air entering the upper portion of the system until the feed problem is corrected. If the feed interruption persists, the volatile material in the furnace is depleted and the temperature profile cannot be maintained by sludge combustion. The operator then actuates the necessary burners to maintain the system's temperature profile. Meanwhile, the emission control system is able to maintain the exhaust gas quality.

Control of the sludge combustion air to the furnace can be accomplished by two methods: automatic controller and manual loading stations and manual valves. The operators currently run the furnace in the manual mode. The automatic system, with the original instrumentation, tended to overcompensate, which resulted in an oscillating temperature profile. Proper tuning of the instrumentation eliminated this problem. The operators do not find temperature control difficult and are able to keep the furnace operating in a stable mode. Another innovative feature of the modified furnace concerns the method of sludge combustion air addition to the upper hearths. Sludge combustion air ports on hearths one through three have been placed there for that purpose, while the mixing jets on hearths one through five were installed only to promote good combustion for burning autogenous sludge. Each 5-cm (2-in) mixing jet line operates at 0.1 kPa (16 oz/in^2) header pressure and discharges a significant amount of air into the hearth when the valve is open. Consequently, the 1.9-cm (0.75-in) mixing jets are used to provide gross temperature control on a hearth, and the sludge combustion air manual loading stations are used for fire control.

The Lansing furnace was not equipped with sufficient instrumentation to verify the ability of the mixing jets to equalize the temperature on a given hearth, but a visual examination did not indicate problems of uneven temperature profiles with the modified system.

Cyclo-Hearth vs Conventional MHF at Lansing. The most significant improvement of the Cyclo-Hearth over the conventional MHF is the degree of operator control over the furnace temperature profile. When burning autogenous sludge, the conventional system was unable to process the material satisfactorily due to inadequate hearth temperature control, which caused clinker formation in the furnace and resulted in frequent shutdowns for removal and high wear rates on the rabble teeth. The modifications provide the needed temperature control at all times, thereby minimizing clinker formation. The modifications also resulted in a system that demonstrates better stability response to feed changes than the previous system. The modified furnace responds to changes in the feed conditions to maintain stable operating temperatures. When processing the superautogenous sludge using the conventional system, operators had considerable difficulty maintaining temperature stability, since the furnace lacked the necessary hardware to effect this type of control. The improved stack emissions of the Cyclo-Hearth over the conventional MHF are the most important results of the modifications. Due to poor temperature control and stability, the conventional system was not able to meet the limit of 0.2 gm particulate/kg dry gas at 50 percent excess air. The performance test for the modified furnace was well under this limit, since 0.032 gm/kg dry gas at 50 percent excess air was achieved.

WASTE HEAT RECOVERY EQUIPMENT

In early 1983, a new installation of four MHFs fitted with waste heat boilers began generating steam at the Metropolitan (Metro) WWTP serving 57 municipalities in the major core of the Twin

Cities area in Minnesota. The plant, located on the Mississippi River in Saint Paul, has a nominal flow rating of 11 m^3/s (250 mgd) and produces 81 Mg/day (90 tons) of raw primary sludge cake conditioned with polymer and 131 Mg/day (145 tons) of thermally conditioned cake. Typical solids content of the primary sludge after dewatering by twin-roll presses is 32-35 percent. Typical solids content of the cake from the thermal conditioning and dewatering process, which handles a blended sludge that is 3 parts secondary to 1 part primary, is also held at 32-35 percent. Process conditions in the dewatering step that employs automated membrane presses can be set to achieve solids content of 55 percent or more, but this burns too hot in the furnace and causes clinkering.

For the first 24 days in January 1984, steam production averaged between 14-18 Mg/hr (30,000-40,000 lb/hr), and total steam produced when valued at the equivalent cost of natural gas that would otherwise be burned in onsite steam generators was worth $113,000. This is based on gas costs of 0.4¢/MJ ($4/MBtu). The 1984 goal is to produce steam valued in this way worth $1.5 million. If valued in No. 2 fuel oil terms at 0.26¢/l ($1/gal), and even allowing for a higher excess air ratio to avoid smoke, this equivalent value would be approximately doubled. The system at the Metro plant consists of two MHFs and two furnaces that had been in service for 13 and 9 years, respectively, plus two 1968 remodeled standby furnaces not fitted with waste heat recovery. All are designed to accommodate autogenous cake plus scum burning. The top hearth receives no feed and is the "zero-hearth afterburner." All have provision for the addition of pressurized sludge combustion air at hearths zero through four, seven, and eight. The waste heat recovery steam generators are rated at 9 Mg/hr (20,000 lb/hr) at 2.8×10^3 kPa (400 psig). Actually, they are delivering at about half of that capacity because of reductions in furnace loading. All steam needed by this thermal conditioning process is supplied by this recovery system, and much of the plant's winter building heat load is also provided. In warmer months, steam will continue to be used for the thermal conditioning process and air-conditioning; the remainder will be used in turbines that drive equipment such as ID fans and boiler feedwater pumps.

Table II-4 lists the locations that have reported good-to-excellent results in the operation of waste heat recovery equipment.

Table II-4. *Successful waste heat recovery installations.*

Generating Steam over 125 psig	Generating Steam up to 125 psig or Hot Water	Heating Air for Combustion Supply
Green Bay, WI	Buffalo, NY	Redwood City, CA
San Mateo, CA	Erie County, NY (South Downs)	Amherst, NY
Cedar Rapids, IA	Kansas City, KS (Plant No. 20)	Tonawanda, NY
Davenport, IA	Louisville, KY	Watertown, NY
Dubuque, IA	Ann Arbor, MI	
Atlantic County, NJ	Duluth, MN	
Honolulu, HI (Sand Island)		
Lansing, MI		
St. Paul-Minneapolis, MN (Metro)		
New Rochelle, NY		
Hopewell, VA		
Campbell-Kenton County, KY		
Niles, MI		

kPa = 0.14465 psi

CHAPTER III. COCOMBUSTION OF SLUDGE AND SOLID WASTES

INTRODUCTION

The rationale for considering the joint combustion of sludge and solid wastes is that sludge, even after dewatering by conventional methods, lacks sufficient heat value to balance the evaporative burden of its remaining moisture when it is burned in a typical combustor. A further disadvantage is usually the need to supply adequate heat to the combustion products and excess air so that odor emissions are minimized. Solid wastes, on the other hand, typically generate more heat than is necessary to burn them to innocuous products. By computation, a heat balance is reached when the per capita quantities of solid wastes and sludge solids are combined, provided that the sludge is dewatered to about 25-30 percent solids. This is an easy task if the sludge is raw primary sludge alone, but the refined dewatering is much more costly if the sludge has been digested or if a companion amount of biological sludge is present. A further complication is that more sludge mass is created when biological treatment is employed, and the overall cake from any dewatering process, except that preceded by heat conditioning, is generally wetter. Thus, the technical feasibility of cocombustion without the need for auxiliary fuel has to take into account the treatment plant process train.

The trend toward cocombustion in those European countries where incineration is a well-established and widely applied technology is a natural progression. Solid waste incineration is far less accepted in the United States, and thus joint combustion technology is considered less. In part, this is because many earlier solid waste incinerators were serious air polluters. In Minneapolis, MN, for example, two municipal incinerators that were built in the 1930s under a Public Works Administration program were commonly ignited each day by burning auto tires found in the collection trucks. Public pressure from citizens who were bothered by the air pollution helped bring about a landfill program that began in the 1960s and terminated incineration.

New York City, where a plethora of apartment house incinerators was installed, has historically fought hard against municipal incinerators for refuse or solid wastes and, as a result, public acceptance of sludge incineration in the near future appears unlikely. A major report for the Interstate Sanitation Commission (NY-NJ-CT) proposed sludge combustion but called it "pyrolysis," a hi-tech name used incorrectly in this instance to mean starved-air combustion (SAC). Refuse was to be processed into refuse-derived fuel (RDF) and blended in, as was done in the mid-1970s pilot work in California for the Central Contra Costa Sanitary District. Neither the New York nor the California work has proceeded to full-scale design for both technical and institutional reasons. In Europe, even 20 years ago, incinerators were built to a higher standard of quality, and air emissions were controlled by costly methods. There, the ability to more economically process two waste products at a single site with a single management staff and shared maintenance and support workers is seen as a major advantage; cocombustion also allows a single operating permit to be issued by the regulatory agency. This is much less likely to be realized in the United States, where it is common to have one completely separate entity responsible for the sludge and another one for the solid wastes, with the solid wastes frequently controlled by private ventures rather than public agencies.

Partial appeal of cocombustion rests on the assumption that fossil fuel costs for sludge solids incineration are an insurmountable obstacle and that the heat value of the refuse is needed. However, in recent years, better methods of dewatering sludge have become widely adopted. This was discussed and illustrated with case histories in the previous chapter. Furthermore, the concerns about cost and availability of fuel have dissipated, and, as was shown in the previous chapter, more efficient incinerators for sludge can be designed and older ones can be upgraded. Thus, the technical risks and institutional aspects of a joint combustion facility have taken on a greater significance. Cocombustion of refuse and sludge solids in the United States is currently practiced in only three locations using widely divergent technologies.

COMBUSTORS SUITABLE FOR CODISPOSAL

Most burning has been tried in mass-burn refuse incinerators of the usual configurations adopted for refuse that has had only minimal preparation, such as removal of bulky objects and explosion risks. Incinerators of the water-wall type that are suited for heat recovery are the more modern type, although sludge could also be burned in a refractory-wall type incinerator. The action of the grate, application of combustion air, and the means of dispersal of the sludge are critical elements.

The rotary combustor, a combination of a water-wall incinerator and rotary kiln, has been installed in only one location in the United States (Gallatin, TN) and is currently burning only refuse. It should be excellent for handling a mixture of coarsely shredded, moderately prepared refuse and sludge cake in that it has absolute purging of any noncombustibles. Thermal economy and stability when burning sludge cake along with refuse would have to be proved. This U.S. installation has been found to be too small to allow adequate burn time for raw refuse.

The modular refuse incinerator is generally much smaller than the typical mass-burn type, and its practicality for codisposal has not yet been proven. However, a well-dewatered cake could be proportioned into the solid wastes/refuse feed and be expected to burn satisfactorily in the available residence time, provided that sludge cake lumps did not "case harden" and leave a core of wet solids surrounded by crust or ash. Agitation of the bed in a modular unit is minimal, and sludge ball discharge with the ash is possible.

Flash-dryer incinerator equipment has been used for many years to dry wastewater sludge, but has been less successful in incineration. Because the process involves suspension burning of fine particles, such a system is not at all suited to mixtures of refuse and sludge. However, it can be used in a design as the method of preparing sludge for mixing with refuse or for injection above the burning refuse in a conventional incinerator. If the flash-drying method is considered, it can be made cost-effective by using recycled incinerator gases as the heat source. If, for example, flue gases pass through a high-pressure boiler and come out at 315° - 370°C (600° - 700°F), there should be sufficient heat energy for an effective flash-drying operation.

The MHF, commonly applied in sludge combustion, is likely to be used if the wastewater agency is in control of design or has such units in service already. In this situation, preparation of the refuse needs to be more elaborate, usually requiring size reduction to 3-5 cm (1-2 in) maximum dimension to minimize fouling of the rabble teeth, unless metals are effectively taken out by air classification. The furnace is self-clearing of noncombustibles if the ash system has been designed appropriately. European experience indicates that best performance is obtained if sludge cake is fed to the top hearth and the RDF is fed to the normal combustion hearth. Flashback fires must be guarded against in the RDF injection design.

The FBF was installed and operated as a cocombustion demonstration facility at both Duluth, MN, and Franklin, OH. As noted previously, any design must deal with the noncombustibles that especially tend to collect in a FBF rather than purge out automatically as in a traveling grate or multiple-hearth unit. However, this problem can be materially lessened with proper design. At Duluth, the problem of noncombustible matter collecting in the bed was aggravated by the design inadequacy of the classifier built into the secondary shredder. This caused a greater loading of noncombustibles than was expected. It was one of many materials handling aspects in the solid wastes/refuse train that delayed the successful operation of codisposal and was not attributable to the selection of a FBF. Similar problems at Franklin, OH, were solved within the first few years; then the system ran well until shutdown (for other reasons) in the late 1970s.

Predrying the Sludge Solids

In the design of a cocombustion system, the thermal balance must account for the water present in the sludge stream. If heat is to be recovered from the hot gases or if odor control considerations require some preselected flue gas temperature, then the presence of more moisture than can be tolerated will mandate that a drying step follow the dewatering of the sludge.

A further factor is the chosen means of combustion. Is it by suspension firing or burning on a grate along with the refuse? Firing in suspension implies that the sludge solids enter the furnace from the top, as a free-flowing granular or powdered product. This usually means that the residual moisture has been brought down to the 5-25 percent range, which dictates the use of a direct drying or multieffect evaporation step.

If grate firing is planned, a conventional dewatering step may be sufficient, as is employed at Glen Cove, NY. It is necessary to get the sludge solids distributed evenly over the refuse charge. If water reduction beyond that achievable by conventional dewatering is dictated by the process' thermal balance, drying to 30-50 percent residual moisture may be sufficient. This can be accomplished by indirect drying equipment, although such systems as applied in chemical, pharmaceutical, and food industries have not been economically or technically attractive to the wastewater treatment industry for sludge use. Virtually all the sludge drying that is done in the United States, whether for cocombustion (Stamford, CT; Flint River, GA) or marketing of a sludge product (Houston, TX; Milwaukee, WI; Chicago, IL; Largo, FL), is by the direct drying method. A rotary dryer system of two units was installed in 1982 at the Metropolitan WWTP serving the Saint Paul-Minneapolis area. However, it is expected to be used only as a contingency mode of sludge disposal or if an agricultural-use market is identified. At Harrisburg, PA, trials of an indirect drying device, termed a hollow-flight jacketed dryer, have not given good results.

In short, drying of sludge makes cocombustion easier, but the need for the added capital investment and the incurring of operating and maintenance (O&M) costs have to be justified by the value of the heat that is not needed for evaporation of water in the combustor. Energy is also required for the heating of water vapor to flue gas temperature or, at a minimum, to the exit temperature of a waste heat recovery device. Thus, the design decisions for a sludge drying process involve the same reasoning as for applying a waste heat recovery system: the value of the heat and whether it can be used beneficially.

U.S. COINCINERATION SITES

The following section describes the coincineration practices at several sites in the United States. Case histories are presented for systems at Stamford, CT; Glen Cove, NY; Duluth, MN; Flint River, GA; and some trial operation sites in the United States.

Stamford, CT

This coincineration system is the only operational one of its kind in the United States. It was proposed in 1968, put into operation in December 1974, and has been operational ever since. Sludge for this process is produced at the city's 0.9 m^3/s (20-mgd) conventional activated sludge treatment plant. Using progressive cavity pumps, the mixture of primary and secondary sludges is pumped to belt filter presses. Approximately 7.6 m (25 ft) upstream of the belt filter presses, polyelectrolyte is added into the sludge piping. This point of addition allows for better mixing of the sludge and polymer. The conditioned sludge is dewatered to an average cake solids concentration of 26 percent. The cake is discharged to a pug mill, where it is combined with previously dried sludge to produce a mixture with a solids concentration of approximately 65 percent. This mixture is then conveyed to a rotary dryer. A portion of the hot gas that would normally be wasted through the solid waste incinerator stack is tempered with ambient air and introduced into the dryer at about the same location as the sludge mixture. As the dryer rotates, the sludge is cascaded through the hot gases, and moisture is evaporated at a rate of 2,300-3,200 kg (5,000-7,000 lb) of water per hour. The dried sludge, with a solids content of 90 percent, is discharged through a diverter gate and divided into two streams, one of which is recycled to the pug mill while the other is conveyed to the incinerator and burned. The heat value of the sludge averages 20,930 kJ/kg (9,000 Btu/lb) of volatile solids.

The incinerator is a conventional mass-burning refuse incinerator with rocking grates. It has a capacity of 330 Mg/day (360 tons/day) and uses electrostatic precipitators for pollution control. The refuse/solid waste as received with no pretreatment has a heat value as fed of 14,000 kJ/kg (6,000 Btu/lb). It enters the incinerator through a charging hopper and is discharged onto the grates at a rate of approximately 180 kg/min (280 tons/day). At preset intervals, the grates rock, thus moving the burning material through the furnace. Combustion is controlled using overfire and underfire air fans. At the end of the furnace bed, the ash drops into a wet sluice and is conveyed to a truck for landfill.

The dried sludge, at a rate of about 9.5 kg/min (15 dry tons/day), enters the furnace through ports in the ceiling and burns in suspension within the first 1m (3 ft) of drop. The hot gases for the drying system are drawn from the incinerator at 980°C (1,800°F) at a rate of about 6.1 m^3/s (13,000 cfm) and are reduced to 200° - 400°C (400° - 800°F) by adding ambient air. This temperature is controlled by the dryer exhaust temperature, which is set at 66-79.4°C (150° - 175°F). As the hot gases pass through the dryer, they pick up moisture and dust which must then be removed in a cyclone dust collector. These gases are then returned to the furnace for deodorization.

Soon after this system went into operation, it became obvious that several modifications had to be made to enable the system to work effectively. Many of these were quite simple and most were designed and installed by plant personnel. The coincineration system was installed in the existing incinerator building. Because space was limited, it was necessary to spread the equipment over five different floor levels. Many conveyors were needed to move the sludge from one stage of the process to another, thereby increasing material handling problems.

At various stages in the system, samples were taken to determine material moisture. It was observed that as material moisture increased, the amperage of the conveyor motors increased. In addition, if the operator tried to process too much sludge, the amperage would also increase. Using these facts, an amperage range was established for ideal sludge moisture content and volume. Portable ammeters were used for the determination. After operating for several days to prove that these ranges were correct, permanent ammeters were installed at the main control panel to monitor the pug mill and all critical conveyors. These allow the operator to control the process from the main panel and determine whether to increase or decrease the dry recycle and dewatered cake rates on the basis of the amperage reading. This has reduced operator fatigue and allows for a more stable process. The operator is still required visually to inspect the entire system but at much less frequent intervals.

Clogged conveyors presented another serious material handling problem. This was caused by rag buildup on the bearings, changes in the material characteristics, and broken drive belts. As the conveyor began to get clogged or if the drive belts broke, the rotational speed of the shaft would decrease or completely stop. Again, this was fairly simple to solve. By attaching speed sensors to the drive shafts of the gear reducers, this decrease of speed could be sensed. Now, as soon as the speed decreases below a certain point, the electrical interlock system shuts down the material feed to that conveyor and an alarm rings at the main control panel, alerting the operator and allowing him to take action before any serious equipment blockages occur. Because of this, downtime has been greatly reduced, and the operator is no longer faced with the frustration of having to remove compacted sludge from the conveyor.

Another material handling problem was caused by the thixotropic nature of dewatered sludge cake; that is, the sludge would change in viscosity as stress was applied. A screw conveyor approximately 20 m (65 ft) long was used to convey the dewatered sludge from the presses to the pug mill. Problems were encountered almost immediately. The physical characteristics of the sludge cake began to change dramatically as the sludge proceeded through the conveyor. The sludge became very sticky, making it difficult to convey and causing excessive torque on the drive motor. It was virtually impossible to run the system. The screw conveyor had to be replaced by a belt conveyor that would not alter the physical characteristics of the sludge. Short screw conveyors for dewatered cake do not seem to affect the sludge characteristics, but as the length of the conveyor increases, this problem becomes more evident.

Dewatered cake dryness and polymer concentration in the cake also appear to have considerable effects on the ability of the system to function. Instead of the usual type of dried material, which is light and fluffy somewhat like the material inside a vacuum cleaner, the sludge begins to form balls, initially about the size of peas. These balls are dry on the outside and moist on the inside. As these balls circulate through the drying system, they get larger and larger. Surface area is reduced considerably, resulting in a greater recycle ratio by weight. This, at times, also makes the system virtually impossible to operate. High polymer dosages also tend to make the sludge sticky, creating drag on the conveyors and difficulty in mixing in the pug mill. Experiments have shown that these changes occur as the cake solids concentrations drop below 22 percent or the polymer dosage increases beyond 10 gm/kg (20 lb) of dry polymer per kg (ton) of dry sludge. Therefore, when designing this type of system it is important that dewatering equipment is specified that will obtain the desired cake solids. Care in selecting and evaluating polymers will ensure dosage below this level.

Fires were another serious problem. Most of the fires occurred inside the dryer. To control these, an automatic water spray system was devised that includes a spray bar located across the diameter of the feed end of the dryer and two sprays located at the discharge end of the dryer. It was critical that no water from the spray system be allowed to impinge on the periphery of the dryer, since thermal shock could possibly cause damage. Five stainless steel fogging nozzles are spaced evenly along the spray bar. Three nozzles are adjusted to spray the length of the dryer and two are adjusted downward. The sprays are controlled by a thermocouple in the exhaust end of the dryer. When the temperature exceeds the set point of 150°C (300°F), a solenoid opens, allowing water to flow through the sprays, which are set to pulse in intervals of 10 seconds on and 5 seconds off or can be run continuously in a manual mode. The nozzles at the discharge end are also connected to this system. The combination of the sprays has effectively controlled most fires.

Additional minor problems included spalling of metal from the dryer riding rings and hot spots in the live-bottom storage bin. The problem of spalling was corrected by the installation of graphite blocks on each of the four trunnion rolls. This small amount of continuous lubrication has prevented serious wear on the rings. The hot spots in the corners of the live-bottom bin, which were a source of smoldering sludge, were corrected by welding a sheet of metal inside the bin to round the corners preventing a buildup of hot recycled sludge.

In conclusion, although many operational problems have occurred with this system, most of them have been solved, and the system now runs effectively and efficiently. When the plant was built, the coincineration system was the only means of sludge disposal. An alternative method was added to provide backup for the coincineration system. This alternative method is a postdewatering lime stabilization system that costs approximately $1 million/yr to operate, mostly due to the cost of trucking the sludge 65 km (40 miles) to the only available landfill site. The coincineration system is extremely economical and energy conservative, since neither the incinerator nor the dryer requires any external fuel source. It has not added any additional ash handling problems, and it is not a source of air pollution. Additionally, the dried sludge before incineration can be used as a soil conditioner where a market is available, thus creating a source of revenue for the municipality. Furthermore, excess waste heat can be used to generate steam or electricity, which could supply the municipality-owned buildings, with the excess being sold to the public utility. The experience at Stamford indicates that coincineration can be a viable means of sludge disposal.

Glen Cove, NY

One of the newest installations in the United States for joint combustion of refuse and sludge solids is at Glen Cove, NY. This design is different from those at Stamford, CT, Flint River, GA, and Duluth, MN, in that here the sludge is dewatered by centrifuge and fed in semiliquid form at 15-25 percent solids directly onto the refuse charge. The intent of the design is that it will evenly distribute the sludge as a layer on top of the charge, with the sludge having a fuel value that is fairly proportional to that of the refuse on a unit area basis. The Glen Cove plant has two mass-burning furnaces, each designed for a daily feed of 100 Mg (110 tons) of refuse and 14 Mg (15 tons) of centrifuge cake at 20 percent solids, or 3 Mg (3 tons) of dry sludge solids per day. If the refuse is assumed to have 28 percent moisture, the dry weight ratio is 24 to 1 as compared to a wet weight ratio for both of 7.3 to 1. If the refuse, as received, is compared to dry sludge solids, the ratio would be 37 to 1.

Because the Glen Cove WWTP is not receiving flow as high as its design rate, the amount of sludge to be disposed of is much less than the design basis. Actually, only about 2.7-7.2 Mg/d (3-8 tons/day) of 18-20 percent solids centrifuge cake are being fed to the furnaces, which are burning refuse at their design rate total of 200 Mg/d (220 tons/day). Thus, the charging ratio is higher than design, so the sludge is being handled readily. As a result, the operation of this system is not presently representative of the per capita ratio of about 14 lb of dry refuse to 1 lb of dry sludge, expressed on the "as received refuse to sludge dry solids" basis. Instead, there is so much excess refuse compared to sludge that the ratio is greater than 50 to 1. This does not represent a fair demonstration of the adequacy of this design to handle a balanced per capita basis feed.

The Glen Cove furnaces are the refractory-lined, mass-burning type, equipped with "Kascade" stokers and automatic combustion air controls to maintain uniform combustion temperatures and conditions. Each furnace is equipped with a 9,080 kg/hr (20,000 lb/hr) convection boiler rated for 41 kg/cm^2 (600 psi) at 250°C (480°F). Available steam is converted to electric power in a 2,500 kW multistage condensing turbine generator set, which powers the complex of incineration facility and the adjacent wastewater plant. Excess power can be sold to the Long Island Lighting Company. The design basis sludge/refuse mixture has an average high heat value of 9,500 kJ/kg (4,100 Btu/lb). This presumes 11 Mg (12 tons) of water and 3 Mg (3 tons) of sludge solids in the sludge stream to each furnace. Of course, if the sludge is wetter than the 20 percent level, this heat value would be reduced. At 16.7 percent, for example, there would be an extra 3 Mg (3 tons) of water to be evaporated, which would reduce the heat recovery potential and thus the yield of electric power. At 15 percent solids, there would be an extra 4.5 Mg (5 tons) of water to evaporate. The incentive, then, is to maximize the solids in the centrifuge cake consistent with getting even distribution over the refuse charge. Sludge cake above the 20 percent solids level is only achieved when straight primary sludge is centrifuged.

Air pollution control is for particulates only, using two field electrostatic precipitators, each sized for 14,160 L/s (30,000 scfm) at 316°C (600°F). The performance guarantee is to achieve 0.11 g/m³ (0.05 grains/scf) at 12 percent carbon dioxide. The long-term performance of this particulate removal system will be followed with interest by professionals in the wastewater field, where wet methods of scrubbing are universally applied to sludge combustion gases.

Both the coincinerator system and the wastewater plant are operated for Glen Cove under contract by a private company. The city estimates a savings of $700,000 per year compared to prior costs for wastewater and refuse management. The project cost was $24 million.

Fluidized-Bed Coincinerator at Duluth, MN

Because of the fuel oil shortages resulting from the oil embargo of 1974, the Western Lake Superior Sanitary District in Duluth, MN, and the district's consulting engineers decided to utilize available solid waste as auxiliary fuel to incinerate sludge produced at the wastewater treatment facilities. The construction of the facilities was completed in 1979, and the startup began in November 1979. Performance tests were conducted in June 1980.

The Duluth installation consists of two systems, each having a CWB-type conventional fluidized-bed reactor with a 6-m (20-ft) diameter bed and 10-m (34-ft) diameter freeboard, dual gas cyclones, waste heat boiler, Venturi scrubber gas cooler, fluidized air blower and induced draft (ID) fans, and heat exchanger for plume suppression (Figure III-1). The fluidized air blower, ID fan, and some pumps are driven by steam turbines powered by the steam from waste heat boilers. The waste heat boilers are rated for 21,792 kg (48,000 lb) of steam at 19 kg/cm² (280 psig). The boilers are the two-drum, water-tube, natural circulation type, designed for 870°C (1,600°F) gas inlet. The units are equipped with soot-blowing capabilities. The sludge was to be fed into the fluidized-bed reactor through a feed chute at the top of the reactor, and the refuse derived fuel (RDF) was to be fed with a pneumatic solid waste feed system for injection into the freeboard approximately 0.6 m (2 ft) above the fluidized bed, pointing downward to the bed. The gas-cleaning equipment consists of dual gas cyclones, a Venturi scrubber, and a collector/cooler with three impingement plates. The system includes a hydraulic ash handling system consisting of an ash slurry tank, an ash classifier, and a fine ash thickener. The RDF preparation system includes coarse and fine shredders, air classifier, magnetic separators, conveying and metering equipment, and a storage silo.

After completing construction and making the system operational, various attempts were made to incinerate RDF without the sludge. Troubles developed in the RDF feed system, and undesirable "freeboard burning" was experienced (i.e., combustion occurred too high in the furnace). As a result of a malfunctioning air classification system, large metal or wood objects constantly jammed the rotary air lock at the RDF pneumatic feed system. The secondary shredder was designed to shred 95 percent of the material to a size of less than 3.8 cm (1.5 in) in effective diameter. The solid waste processing facilities had no presorting capability. Therefore, glass and other noncombustible objects entered the primary shredder and were broken up and imbedded in the RDF. The location of the RDF feed nozzle was incorrect. The majority of RDF burned in the freeboard area, while fuel oil had to be burned to maintain reasonable bed temperatures. The addition of sludge, by dropping sludge cake into the bed, made the situation worse. While trying to keep the bed hot by burning fuel oil, the startup operators were also trying to keep the freeboard cool by spraying a fine spray of water in the reactor. Fortunately, there was an alternate RDF feed nozzle located near the top of the fluidized bed and directed downward to the bed. The point of entrance into the reactor

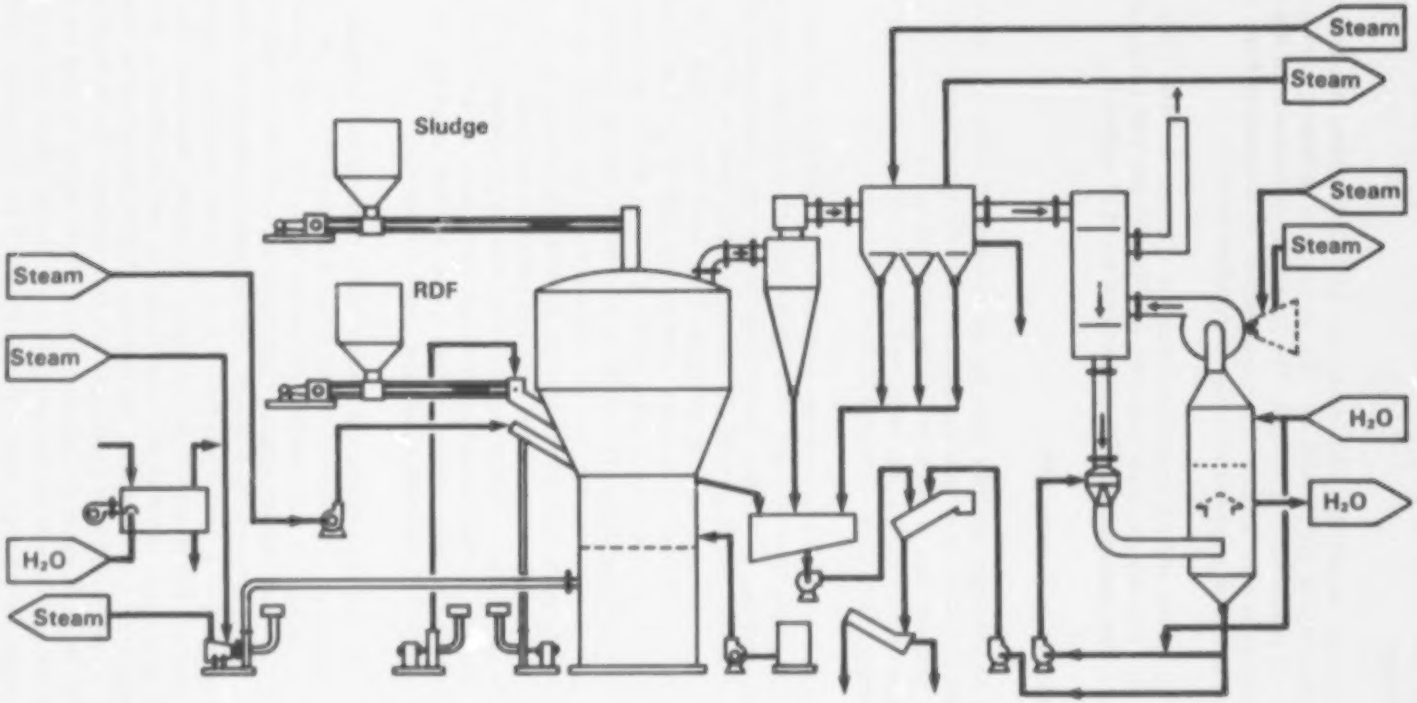

Sludge
RDF
Steam
Steam
H$_2$O
Steam
Steam
Steam
Steam
Steam
H$_2$O
H$_2$O

Figure III-1. Sludge/RDR waste to energy flow sheet.

was approximately 0.6 m (2 ft) below the top of the bed when the fluidized-bed height is 2 m (6 ft). Although use of this optional feed location made considerable improvement, the freeboard temperatures were not controllable when coincinerating sludge with RDF. Also, the necessary bed temperature for combustion could not be sustained when coincinerating.

It became apparent that using the single RDF feed port at the lower location did not satisfy the original design intent of coincinerating RDF and sludge cake in the bed. Multiple feed points for RDF needed to be developed. The first approach was to modify the sludge feed port and utilize the moisture content of sludge to control the freeboard temperature in lieu of freeboard sprays. A series of attempts were made to spread the sludge over the freeboard. Finally, a special nozzle was developed to feed the sludge in a small enough particle size to allow the water to evaporate and a large enough size to have solids end up in the bed to complete incineration. The feed device developed produces sludge particles approximately 0.3 cm (1/8 in) in diameter most of the time. Steam is utilized to shear the sludge after it is extruded through a converging nozzle. The extruded flow is not even, and periodic surges of dispersed sludge take place. With the new sludge feed device and the RDF feed nozzle, experiments were made with the height of the bed. The bed was allowed to grow as deep as permitted by the capacity of the fluidizing air blower.

Performance tests successfully demonstrated that the system could operate at design rates while meeting particulate emission requirements. They also showed that the system was capable of incinerating sludge with fuel oil, sludge with RDF, RDF alone, or all fuels at one time and at adjusted loading rates. Table III-1 shows the average quantities of RDF sludge, and fuel incinerated during tests. The design capacity tests were conducted for an 8-hour duration. Ash collected during the test was analyzed in detail and results are shown in Table III-2. Results of emission tests and exhaust gas composition are shown in Table III-3. While coincinerating sludge with RDF, the excess air rate was between 48 and 51 percent. The excess air rate during incinerating sludge with fuel oil was about 85 percent. While burning RDF without sludge, fluidizing and cooling requirements resulted in high levels of excess air. The amount of excess air used during the RDF-only mode was 174 to 232 percent. The visible emissions from the stack were limited to 20 percent opacity. During the tests, 98 percent of the time the opacity was within 10 percent, and only during the last 7 minutes of the sludge/RDF test did the opacity exceed the 20 percent limit.

During the startup and testing period, the ash handling system was very difficult to operate. The fine ash thickener continually plugged up, and a small wet cyclone eventually had to be added to the system to relieve the problem. The fine ash refused to settle in the ash classifier, and the cyclone dip legs had a tendency to plug near the ash quench tank. In addition, the inert fraction of the RDF was too big to be elutriated, and the bed continued to grow in size. Arrangements were made to remove some of the bed regularly, which further aggravated the ash system operation.

During the startup and test burning RDF-only mode, one of the gas cyclones plugged with slag. The material looked like lava and was named "moonrock" by the plant personnel. It was at least 0.9 m (3 ft) high and located at the bottom of the cyclone. The sample of slag was very hard, black in color, shiny, and amorphous.

It appeared that the slag material contained some amount of alkali metal silicates, which became sticky viscous glass when heated. Although there were considerable amounts of Al_2O_3, CaO, and Fe_2O_3 present to react with low-melting, alkali metal silicates like $Na_2O \cdot 3SiO_2$, there were not enough quantities to convert all of the metal silicates to metal oxide-alkali oxide-silica dioxides. The retention time in the bed was not long enough to complete the reactions, and burning was taking place in the ducts and cyclones. The residual amount of low-melting, alkali-metal silicates caused the ash to agglomerate in the cyclones.

Table III-1. *Average quantities of refuse-derived fuel, sludge, and fuel incinerated during the performance tests.*

	Wet lbs/hr	Dry lbs/hr	Percent Solids	Percent Volatiles	Heating Value Btu/lb
Refused-derived fuel	17,700	12,938	76.66	68.83	8,652
Sludge	27,217	5,852	21.50	56.30	10,468
Refused-derived fuel	5,285	3,932	74.22	69.47	8,963
Sludge	15,778	3,281	20.34	63.62	10,735
No. 2 fuel oil (gal)	338	—	—	—	19,400
Sludge	29,880	6,884	23.00	58.80	9,884
Refused-derived fuel	13,787	10,453	76.10	67.20	9,464

Note: lb × 0.454 = kg
Btu/lb × 2.3255 = kJ/kg

Table III-2. *Ash and bed analysis*[1]. *(Percent)*

Sample Elements[2]	Bed Material 4/25/80	Bed Material 4/26/80	Cyclone[3] Deposit 4/28/80	RDF Ash[4] 4/25/80
Si	P.C.[5]	P.C.[5]	P.C.[5]	P.C.[5]
Al	6.0	3.5	17.5	8.5
Fe	2.5	3.5	5.0	5.0
Ca	7.5	7.5	10.0	8.5
Mg	1.0	0.85	1.5	1.25
Na	2.5	2.25	4.0	5.0
K	0.5	0.5	3.5	4.0
Ti	0.4	0.7	1.25	0.85

[1] During RDF incineration without sludge; semi-quantitative spectrographic analysis

[2] As Oxides

[3] Melting point of material is 1,000°C (> 1,832°F)

[4] Residue after ignition @ 590°C (1,100°F) is 22 percent w/w

[5] Principal constituent

Table III-3. *Results of emission tests and exhaust gas composition.*

FILTERABLE PARTICULATE CONCENTRATIONS AND EMISSION RATES

	Concentration GR/DSCF	Emission Rate lb/ton dry feed
Sludge with refuse derived fuel	0.028	0.468
Sludge with fuel oil	0.024	0.901
Refuse derived fuel	0.009	0.234

Note: 1 grain = 0.065 grams
1 cubic foot = 28.32 liters
1 lb/ton = 0.5 gm/kg

EXHAUST GAS COMPOSITION* (Percent Volume)

	CO_2	O_2	CO	Balance	Moisture
Sludge with refuse derived fuel	11.5	7.2	< 0.1	81.3	26.55
Sludge with fuel oil	7.9	10.0	< 0.1	82.1	12.1
Refuse derived	6.0	14.2	< 0.1	79.8	9.9

*At scrubber exhaust, dry basis except percent v/v moisture

At the time the tests were conducted, $FeCl_3$ and lime were being used to condition the sludge for vacuum filtration. It was known that the addition of both Fe and Ca would help to further convert the remaining alkali metal silicates. CaO with sodium silicate will form Devitrite ($Na_2O \cdot 3/CaO \cdot 6SiO_2$), which melts at 1,030° C (1,886° F); Fe_2O_3 reacts with sodium silicate to form Acmite ($Na_2O \cdot Fe_2O_3 \cdot 4/SiO_2$), which melts at 955°C (1,751°F). With this assumption, it was decided to continue the coincineration tests after the slag was removed from the cyclone. The addition of limestone and clay to the feed to prevent this scaling gave encouraging results. Similar results were reported using clay as an additive when incinerating sludges high in sodium. This eliminated the buildup of molten salts on the bed particles and the resultant bed stickiness. During the sludge/RDF coincineration, no slagging problems were encountered. Immediately after the completion of the performance tests in July 1980, the solid disposal facility was shut down for modifications to the RDF preparation and the ash handling systems.

In conclusion, the startup and modification work at Duluth showed that processed refuse and wastewater sludge cake could be coincinerated and produce recoverable energy while meeting permit standards for air emissions. In early 1984, the district purchased wood chips and bark waste from forest product plants in the vicinity and began coincinerating this material with sludge cake. New belt presses have been started up successfully, replacing the vacuum filters in service, and the resulting cake is higher in the ratio of volatile solids to moisture. Presently, the cost of the added fuel in the form of wood industry waste is about $10/ton of wet cake at 16-18 percent solids. This is considered less expensive than the cost of processing refuse in the RDF-making facilities.

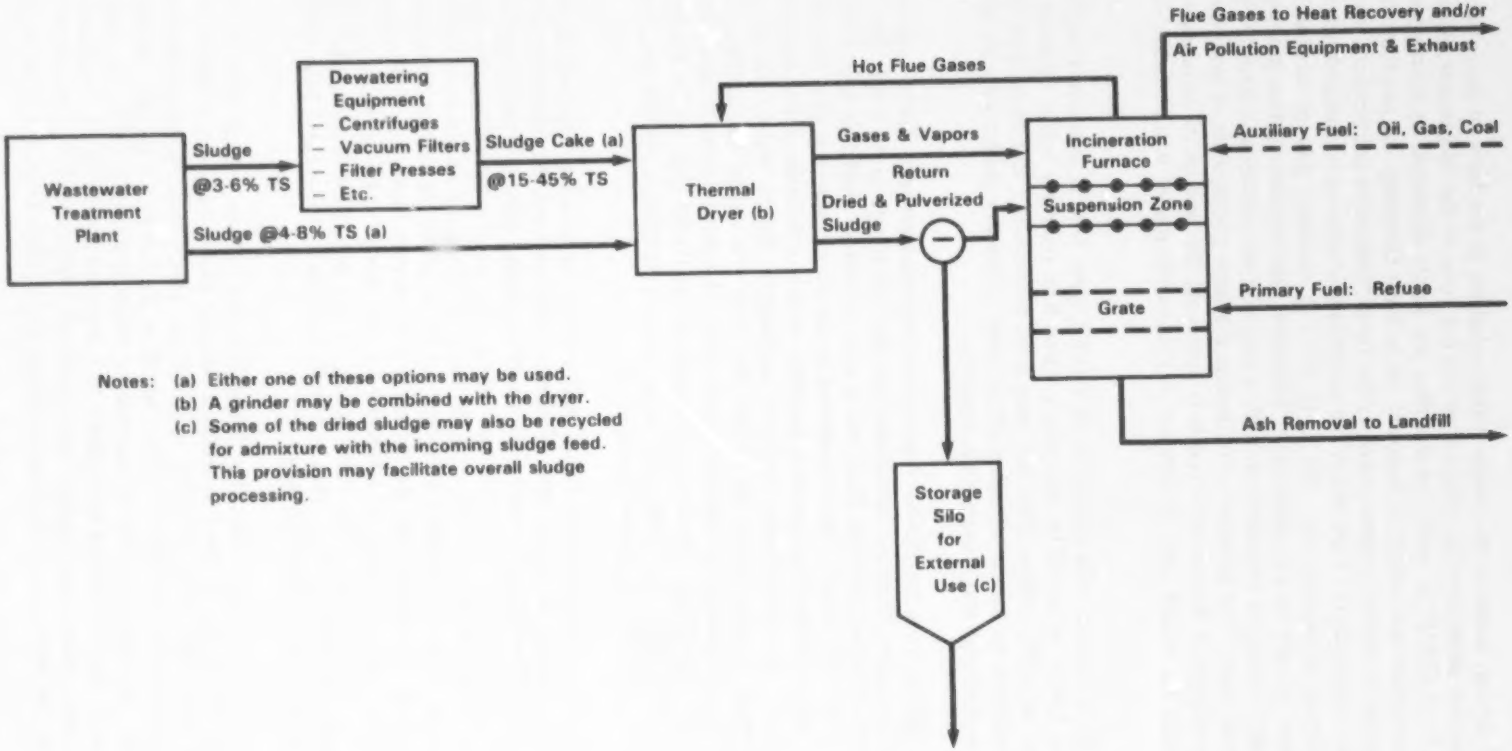
Coincineration at Flint River, GA

The incineration of sludge solids and green wood chips at the Flint River WWTP in Clayton County, GA, differs from the other U.S. projects described in that the sludge is dried and pelletized before being fed to the combustor. The hot gases from the Pulse Hearth™ furnace are used to dry the sludge in rotary triple-pass Heil dryers. The furnace system was started up in late 1982; the dryers were existing equipment that had previously been heated by natural gas. The rated capacity of the system is 25,000 MJ/hr (24 million Btu/hr) input. Two furnaces are arranged in series and produce a 980°C (1,800°F) off-gas temperature that is tempered down to 540°C (1,000°F) by mixing with ambient air before entering the dryers. Exit gases are wet-scrubbed with water only, at a pressure drop of 15 inches water column, and the air emissions limit of the plant is met. No significant odor complaints have been reported. The manufacturer of the furnace claims that the multipass design of the combustion chamber allows controlled burning of the sludge pellets and wood chips without creating submicron fines or permitting unburned hydrocarbons to escape. Selection of a cocombustion system like this would be most attractive in an area where forest products are manufactured and where a steady supply of the wood chips at an attractive cost can be assured. This is the case at the Duluth installation.

TYPES OF CODISPOSAL SYSTEMS IN THE UNITED STATES AND EUROPE

Although there are a number of different approaches to codisposal by incineration, most of them can be categorized into four basic types: Direct Drying - Suspension Firing (DD-SF); Indirect Drying - Suspension Firing (ID-SF); Direct Drying - Grate Firing (DD-GF); and Indirect Drying - Grate Firing (ID-GF). Each of the four types involves predrying the sludge cake before feeding it to the combustion chamber. A fifth type, that does not involve sludge cake predrying, is exemplified by the Glen Cove, NY, and Duluth, MN, projects in the United States but is not readily evident in European practice.

Figure III-2 illustrates the DD-SF type, where sludge coming from a wastewater treatment plant (WWTP) is fed into a thermal dryer prior to incineration. In some cases this occurs directly, whereas in other cases preliminary dewatering is accomplished by mechanical means *before* thermal drying. Often a conditioning agent, such as a polyelectrolyte (polymer), is added to facilitate mechanical dewatering. Because these agents are of an organic nature, they do not adversely affect subsequent incineration. Inorganic agents such as lime and ferric and aluminum salts would be detrimental to heat value but may prevent rapid slag formation and be beneficial in that way. However, chloride content is very undesirable. In the dryer, the solids concentration of the sludge is raised typically to the 75-95 percent level. To promote drying by assuring proper consistency, the feed sludge is often ground and mixed with a recirculated portion that is already dry. Finally, the sludge powder is injected or blown into the incinerator in a zone above the burning refuse. Most of the sludge powder burns in suspension, and complete destruction of all putrescible matter is virtually assured. The energy required for drying the sludge is provided by removing a portion of hot flue gases that are then directly brought into contact with the wet sludge. The quantity of flue gases must be sufficient to furnish all the latent heat of vaporization required by the sludge to be dried. This heat must be dissipated by evaporating water before the sludge gets dry enough to catch fire or explode.


Wastewater Treatment Plant
Sludge
@3-6% TS
Sludge @4-8% TS (a)
Dewatering Equipment
– Centrifuges
– Vacuum Filters
– Filter Presses
– Etc.
Sludge Cake (a)
@15-45% TS
Thermal Dryer (b)
Hot Flue Gases
Gases & Vapors
Return
Dried & Pulverized Sludge
Incineration Furnace
Suspension Zone
Grate
Flue Gases to Heat Recovery and/or Air Pollution Equipment & Exhaust
Auxiliary Fuel: Oil, Gas, Coal
Primary Fuel: Refuse
Ash Removal to Landfill
Storage Silo for External Use (c)

Notes:
(a) Either one of these options may be used.
(b) A grinder may be combined with the dryer.
(c) Some of the dried sludge may also be recycled for admixture with the incoming sludge feed. This provision may facilitate overall sludge processing.

Figure III-2. Codisposal incinerators of the DD-SF type.

During thermal drying, some of the sludge solids volatilize in the form of gases and vapors. These highly odoriferous substances are returned to the hot zone of the incinerator, usually at a temperature of 774 °C (1,425 °F) or more, so that they are safely destroyed by thermal means. If the highest degree of environmental control is required, as in West Germany, an auxiliary firing system is installed. A temperature control system monitors the final combustion temperature inside the incinerator. In case this temperature drops below the minimum of what is considered necessary for the destruction of odoriferous substances (i.e., 802 °C [1,475 °F]), auxiliary gas- or oil-fired burners will light up to compensate for any energy deficiency. Thereafter, the mixture of flue gases coming from both refuse and sludge burning is conveyed through a common air pollution control (APC) system out through a common stack. The resultant ash contains the inert constituents of both the refuse and the sludge. If a high degree of thermal destruction is achieved, the amount of carbonaceous matter will be below 3 percent by weight, and the amount of putrescible matter will be below 0.3 percent by weight.

There are two major options with regard to the DD-SF type. One is to recover additional energy for steam generation. This is achieved by inserting a waste heat recovery boiler between the incinerator furnace and the APC system. This has been done successfully and on a large scale in Europe. The other option is to siphon off either all or some of the dry sludge powder and use it as a soil conditioner for agricultural and construction purposes.

The ID-SF type differs from the DD-SF type in one important respect. There is no direct contact between the hot flue gases from the incinerator and the wet sludge to be dried. This is accomplished by means of a heat transfer fluid that is used to extract sufficient heat from the incinerator's hot flue gases. This heat is then transferred to the dryer, where it provides the latent heat of vaporization. The heat recovery equipment is installed on the outlet side of the incinerator. It may include steam generators, hot water boilers, and heat exchangers. Steam, water, and oil are commonly used as the thermal transfer fluids. As before, the gases and vapors that emanate from the dryer are returned to the incinerator for thermal destruction. The dried sludge is also conveyed to the incinerator for suspension firing. The main advantage of the ID-SF type is that sludge drying and sludge incineration are physically separated. This is particularly helpful in retrofit situations, where space limitations require separate equipment installations.

A third type, DD-GF, is considered by many engineers as the simplest approach to sludge disposal in a municipal refuse-fired incinerator. Sludge is received from the treatment plant and partially dewatered by the aforementioned means. The resultant sludge cake is simply transferred to the incinerator and burned together with the refuse on a grate. The precise mechanism by which this sludge is added differs from one plant to the next. In one case sludge is mixed with refuse in the pit, while in another case sludge is dropped into the feed chute above the refuse. Attempts have also been made to simply spray this sludge into the incinerator at various locations. In all cases, the heat needed for vaporization of moisture must be transferred to the sludge cake, or more precisely, to each sludge particle, by direct contact. The effectiveness of any particular approach has aroused controversy among a number of investigators. This is mostly because of the unique heat and mass transfer phenomena which govern sludge drying.

The ID-GF type is similar to the combustor design discussed above, except that, in addition to mechanical dewatering, the sludge is dried by indirect thermal means before it is fed to the incinerator. The ID-GF type lends itself to retrofit applications. Here, heat energy is extracted from the incinerator and transferred to the thermal dryer, which is similar to the process described for the ID-SF type, except that very fine particles are not needed when grate fired and more residual moisture can be tolerated. Indirect drying takes place in a separate device under conditions that can be more closely controlled. Many investigators have established the critical importance of the three T's (temperature, time, and turbulence) in effective sludge processing. Depending on the design features of the dryer, intimate mixing and agitation of individual sludge particles are promoted for maximum thermal efficiency.

U.S. AND EUROPEAN CODISPOSAL INCINERATOR SITES

A number of experiences in burning sludge solids and refuse have been reported over the years. Reasons for the discontinuation of coburning or failures at some of the reporting sites vary; in some cases it was because not enough effort and investment went into the planning and operational stages. Tables III-4 through III-6 are a comprehensive listing of these trials in the United States, and Tables III-7 through III-10 are a listing of those in Europe. Data are presented for the four basic types of codisposal incinerators discussed previously, with the exception that no U.S. incinerators of the ID-SF type were identified.

Case Histories of European Installations

The descriptions of the European cocombustion facilities in this section expand on the tabulated data in the previous section (Tables III-7 through III-10) and should assist in their interpretation. European cities have adopted the principle of cocombustion much more than have U.S. cities. The motivations are intense in Europe, and political jurisdictional problems have not been an obstacle. As a result, solutions have been found that are grounded in technical and economic imperatives. Also, a high quality of construction has been observed by visitors to European installations. The case histories that follow present experiences of cocombustion installations at Bielefeld, Goppingen, and Marktoberdorf in the Federal Republic of Germany and Dordrecht in the Netherlands. A comparative evaluation is then presented of seven additional European mass-burning facilities.

The Bielefeld refuse incinerator consists of three units with a capacity of 16 tons/hr each at a calorific value of 11,000 kJ/kg. With respect to incineration itself, it is a rather conventional plant, consisting of a bunker, the incinerators, boilers, electrostatic precipitators, wet scrubbers, and a specially designed wastewater plant. The four following factors convinced the Federal Government to permit the development: waste was pretreated in order to homogenize it and to mix it with sewage sludge; scrap was separated prior to incineration; hospital waste was incinerated with other wastes; and the wastewater treatment system included flocculation and heavy metal ion exchange processes. The coincineration process design was based on the following throughput:

Household waste	195,000 tons/yr
Commercial waste	85,000 tons/yr
Sewage sludge (40 percent dry matter)	30,000 tons/yr
Hospital waste	10,000 tons/yr

Tons × 0.90718 = metric tons

The investment costs (1983) were 146 million Deutsche Marke (DM) ($58.4 million), about 30 percent of which apply to environmental protection devices. The innovation of interest here is the pretreatment of the waste. Combustion, energy generation, heat exchanger burden, and flue gas cleaning are better equalized than in the incineration of untreated refuse. During the mechanical pretreatment of waste, predried and digested sludge is added in such a way that the mixture could be incinerated on conventional grate systems without difficulties. Scrap is separated before incineration to gain better scrap and less heavy metal emissions in the raw flue gas. Raw waste and the sludge (about 10-15 percent sludge by weight as wet cake containing 40 percent dry matter) are fed into a Losche ball mill, which has an inner diameter of 6.5 m and is filled with 50 tons of 12-cm-diameter balls. Inside the mill, which has an energy consumption of 1 MW and a capacity of 50 tons/hr, the waste is ground and mixed with the sludge. This mixture is then discharged via a trommel screen

Table III-4. *U.S. codisposal incinerators of the DD-SF type.*

			Design Processing Capacities						
Plant	Start-up	Technology Origin	Refuse Processing Lines	Refuse Plant Disposal Capacity	Sludge Processing Lines	Sludge to Refuse Ratio	Energy Recovery	Remarks	Operational Status (8)
Name; State	Year (1)	Vendor (2)	stph (3)	STPD (4)	stph @ % TS (5)	stph/stph (6)	Lb/hr and MW(7)		
Ansonia, CT	1974	Detrick/ Nichols	2 × 4.17	200	1 × 0.38@100	0.15*	Hot gases are exclusively used for sludge drying.	Dried sludge either burnt in suspension or used as fertilizer by highway dept. Spray dryer problems.	NO
Duluth, MN	1980	Copeland	2 × 8.33 (RDF)	400	2 × 7.08@21.5	0.24	2 × 45,000 sat. steam @ 250 psig for inplant use.	Test runs commenced during 1979. Equipment modifications in 1980 and 1982. Full design capacity not yet accomplished.	NO
Franklin, OH	1971	Black & Clawson	1 × 2	50	1 × 0.42@100	0.28	None.	Demonstration plant, now abandoned and dismantled.	NO
Hartford, CT	1957/68	CE Raymond	2 × 6.3	300	1 × 0.286@100	0.06	Only hot gases are exclusively used for sludge drying.	Circular batch-fed incinerators, only one adapted to sludge. 1967 wet scrubber installed, closed 1975.	NO
Holyoke, MA	1965	Pittsburgh	2 × 4.69	225	1 × 0.42@85	0.12*	Hot flue gases are only used for sludge drying.	A third incinerator unit was to be built to eliminate need for supplemental oil firing. Closed 1976 because landfilling was cheaper than upgrading.	NO

Table III-4. *U.S. codisposal incinerators of the DD-SF type. (Continued)*

			Design Processing Capacities						
Plant	Start-up	Technology Origin	Refuse Processing Lines	Refuse Plant Disposal Capacity	Sludge Processing Lines	Sludge to Refuse Ratio	Energy Recovery	Remarks	Operational Status (8)
Name; State	Year (1)	Vendor (2)	stph (3)	STPD (4)	stph @ % TS (5)	stph/stph (6)	Lb/hr and MW(7)		
Rochester, NY (Eastman Kodak)	1970/73	CE and CE Raymond	1 × 7.5	180	1×4.75@20	0.17	135,000 steam @ 400 psig & 550°F for cogeneration.	Uses high Btu shredded commercial & industrial refuse (HHV = 8,800 Btu/lb) supplemental oil firing of about 25% of heat input required.	O
Stamford, CT	1973	Urban Incinerators & CE Raymond	1 × 14.2	340	1×1.33@90	0.11	Hot flue gases are only used for sludge drying.	Operating well, no measurable effect on BSP performance or amount of fly ash produced.	O

NOTES: (1) In case of plant modification and/or expansion, more than one year is listed.

(2) CE Raymond literature lists several other installations of flash dryers for codisposal service: Bloomsburg, PA (1953); Fond du Lac, WI (1951); Louisville, KY (1959); New Albany, IN (1959); Trenton, MI (1964). None of these could be verified and, therefore, they were not included. However, preliminary indications are that these facilities are shut down.

(3) Number of units at short tons per hour each. For example, 3×6.6 means 3 units, each at 6.6 stph.

(4) Short tons per day on a 7-day a week basis.

(5) Number of units at short tons per hour each at the total solids concentration stated in percent. For example, 3×1.0@100 means 3 units each at 1.0 stph when the total solids concentration is adjusted to 100%. This is comparable to bone dry material.

(6) Sludge processing rate per unit in stph and adjusted to 100% TS divided by the refuse processing rate per unit in stph and adjusted to 100% TS. An initial moisture content of 25% H_2O is assumed for raw refuse. N.A. means "not applicable" or "not available." Operating capacity may differ from design capacity and is denoted by an asterisk (*).

(7) Steam generation and electrical power production rates are indicated in lb/hr and MW. For example, 3×40,300 lb/hr means 3 boilers at 40,300 lb/hr steaming capacity each. For example, 2×4.6-9.2 MW means two turbogenerators with a 4.6 MW capability each for a combined capacity of 9.2 MW.

(8) Refers to the status of the sludge processing system only. 0 means "operational," NO means "not operational."

Table III-5. *U.S. codisposal incinerators of the DD-GF type.*

			Design Processing Capacities						
Plant	Start-up	Technology Origin	Refuse Processing Lines	Refuse Plant Disposal Capacity	Sludge Processing Lines	Sludge to Refuse Ratio	Energy Recovery	Remarks	Operational Status (8)
Name; State	Year(1)†	Vendor (2)	stph (3)	STPD (4)	stph @ % TS (5)	stph/stph (6)	Lb/hr and MW(7)		
Pittsfield, MA	1981	(Vicon) Enercon	3 × 5	360	3 × 0.23@40	0.03*	2 × 35,000 sat. steam @ 250 psig for paper factory.	Sludge firing of filter press cake in 1982.	O
Prudhoe Bay, AK	1981	Basic Environmental	1 × 4.42	106	Planning Stage	Planning Stage	40 × 10^6 Btu/hr. water-glycol solution for district heating, includes latent heat of vaporization for sludge drying.	Started operation in Aug. 1981. Addition of second unit planned.	NO
Waterbury, CT	1951/68	Nichols/ CE Raymond	2 × 6.25	300	1 × 2.09@28	0.12	Hot water for in-plant use. None for export.	Burned only primary sludge for vacuum filters. Stopped sludge burning when secondary STP was built with MH furnaces. Burned 3092 STPY sludge in 1973. Also some explosions from grease buildup. Closed 1977.	NO
Whitemarsh Township, PA	1959	Dravo	1 × 12.5	300	2 × 0.5@25	0.11*	Basically none. Only latent heat of vaporization during sludge drying periods.	Successful testing during 1960. Closed 1969.	NO

† See notes at bottom of Table III-4

Table III-6. *U.S. codisposal incinerators of the ID-GF type.*

			Design Processing Capacities						
Plant	Start-up	Technology Origin	Refuse Processing Lines	Refuse Plant Disposal Capacity	Sludge Processing Lines	Sludge to Refuse Ratio	Energy Recovery	Remarks	Operational Status (8)
Name; State	Year(1)†	Vendor (2)	stph (3)	STPD (4)	stph @ % TS (5)	stph/stph (6)	Lb/hr and MW(7)		
Linden, NJ	1978/79	Consumat (Camp, Dresser & McKee)	1 × 2.3	55	1 × 1.02@78	0.461	1 × 1,700 lb/hr saturated steam to provide steam for sludge dryer.	Test program using flue gases plus supplemental digestor gas.	NO
Harrisburg, PA	1972	Martin (Garnett, Fleming)	2 × 15	720	2 × 1.0@15	0.010	2 × 120,000 lb/hr max. @ 250 psig & 525°F used now for district heating system & drying of sludge.	District heating use starting in 1978. Construction completed & sludge firing on test basis started in 1981.	NO

† See notes at bottom of Table III-4

Table III-7. *European codisposal incinerators of the DD-SF type.*

			Design Processing Capacities						
Plant	Start-up	Technology Origin	Refuse Processing Lines	Refuse Plant Disposal Capacity	Sludge Processing Lines	Sludge to Refuse Ratio	Energy Recovery	Remarks	Operational Status (7)
Name; Country	Year (1)	Vendor	stph (2)	STPD (3)	stph @ % TS (4)	stph/stph (5)	Lb/hr and MW(6)		
Bamberg, G	1977/81	Vereinigte Kesselwerke	3 × 6.6	475	3 × 1.0@100 (received @ 40)	0.20	3 × 40,300 of sat. steam @ 370°F for electrical power generation (6) and district heating.	Fully operational together with railroad transportation system for regional waste disposal.	O
Diessenhofen, CH	1974	Von Roll	Used conventional fuels during testing		1 × 0.46@25	N.A.	Hot flue gases are used for sludge drying. Energy recovery for export was not intended.	Pilot plant to do development work for Elberfeld & Vienna (witnessed test program in 1979).	NO
EBS Vienna, A	1980	Von Roll	4 × 15.3	300	6 × 3.19@25	N.A.	2 × 35,200 steam 2 × 64,000 steam @740 psig & 662°F for electrical power generation (2 × 4.6 = 9.2) and district heating.	Regional facility for industrial and municipal waste processing.	
Elberfeld-Bayer, C	1977	Von Roll	Liquid Industrial Wastes		1 × 3.93@14	N.A.	Only latent heat of vaporization for sludge drying from 14 to 98%TS. Energy recovery for export was not intended.	Depending on market conditions, the dried sludge is either used as a soil conditioner or alternatively burnt.	

Table III-7. *European codisposal incinerators of the DD-SF type. (Continued)*

Plant	Start-up	Technology Origin	Design Processing Capacities: Refuse Processing Lines	Design Processing Capacities: Refuse Plant Disposal Capacity	Design Processing Capacities: Sludge Processing Lines	Design Processing Capacities: Sludge to Refuse Ratio	Energy Recovery	Remarks	Operational Status (7)
Name; Country	Year (1)	Vendor	stph (2)	STPD (3)	stph @ % TS (4)	stph/stph (5)	Lb/hr and MW(6)		
Essen-Karnap, G	1961/65	Vereinigte Kesselwerke	5 × 22.0	1,500	5 × 8.6@100	0.52	10 × 220,000 steam @1,421 psig & 950 °F for electrical power generation (5 × 50 = 250).	Operating, will be replaced in future because of old age, also cofires lignite coal.	
Forbach, F	1975/76	Koppers-Wistra (Volund)	2 × 3.3	158	N.A.	N.A.	Hot flue gases are exclusively used for for sludge drying. No energy export.	N.A.	
Ingolstadt, C	1977/81	Widmer + Ernst	3 × 8.3	600	3 × 2.2@100 (received @25)	0.35	Flue gas used for sludge drying. Additionally, retrofit planned for steam generation.	Fully operational, extensive testing by authorities.	
Krefeld, G	1975/80	Vereinigte Kesselwerke	3 × 13.2	950	3 × 3.1@100 (received @26)	0.31	3 × 92,400 steam @363 psig & 707 °F for electrical power generation (2 × 1.4 + 1 × 11.5 = 14.3) and district heating.	Fully operational with municipal refuse and primary sludge. Secondary sludge was added earlier in 1983 when construction of new wastewater treatment plant was completed.	
Lipperswil, CH	1973	Von Roll	Used conventional fuels during testing		1 × 0.46@25	N.A.	Flue gases used for sludge drying.	Pilot plant to do development work for Elberfeld & Vienna (witnessed test program in 1979).	

Table III-7. European codisposal incinerators of the DD-SF type. (Continued)

Plant	Start-up	Technology Origin	Design Processing Capacities: Refuse Processing Lines	Design Processing Capacities: Refuse Plant Disposal Capacity	Design Processing Capacities: Sludge Processing Lines	Design Processing Capacities: Sludge to Refuse Ratio	Energy Recovery	Remarks	Operational Status (7)
Name; Country	Year (1)	Vendor	stph (2)	STPD (3)	stph @ % TS (4)	stph/stph (5)	Lb/hr and MW(6)		
Munich III, G	1982	Vereinigte Kessel-werke/ Martin	2 × 22.0	1,060	2 × 13.2@25	0.20	2 × 127,600 steam @580 psig & 752°[illegible] for electrical power generation (1 × 26 = 26).	Under construction, testing expected to begin early in 1983.	
Solothurn, CH	1973	Von Roll	2 × 11.0	530	N.A. (Planning Stage)	N.A.	2 × 121,400 steam @551 psig & 707 °F for electrical power generation (1 × 10.4 = 10.4).	The incinerator is located on the same premises with WWTP; turbine uses river water for condenser cooling.	
Veurne, B.	1979	Koppers-Wistra (Volund)	2 × 7.7	370	N.A.	N.A.	None, except that flue gases provide heat of vaporization for sludge drying.	N.A.	

NOTES: (1) In case of plant modification and/or expansion, more than one year is listed.
(2) Number of units at short tons per hour each. For example, 3×6.6 means 3 units, each at 6.6 stph.
(3) Short tons per day on a 7-day a week basis.
(4) Number of units at short tons per hour each at the total solids concentration stated in percent. For example, 3×1.0@100 means 3 units each at 1.0 stph when the total solids concentration is adjusted to 100%. This is comparable to bone dry material.
(5) Sludge processing rate per unit in stph and adjusted to 100% TS divided by the refuse processing rate per unit in stph and adjusted to 100% TS. An initial moisture content of 25% H_2O is assumed for raw refuse. N.A. means "not applicable" or "not available."
(6) Steam generation and electrical power production rates are indicated in Lb/hr and MW. For example, 3×40,300 Lb/hr means 3 boilers at 40,300 Lb/hr steaming capacity each. For example, 2×4.6=0.2MW means two turbogenerators with a 4.6 MW capability each for a combined capacity of 9.2 MW.
(7) Refers to the status of the sludge processing system only. O means "operational." NO means "not operational."

Table III-8. *European codisposal incinerators of the ID-SF type.*

			Design Processing Capacities						
Plant	Start-up	Technology Origin	Refuse Processing Lines	Refuse Plant Disposal Capacity	Sludge Processing Lines	Sludge to Refuse Ratio	Energy Recovery	Remarks	Operational Status (7)
Name; Country	Year (1)*	Vendor	stph (2)	STPD (3)	stph @ % TS (4)	stph/stph (5)	Lb/hr and MW(6)		
Fuerstenfeld-bruck	1975	Vereinigte Kessel-werke	1 × 6.6	160	2 × 3.96@50 thin film evaporators 1 × 1.26@80 grinder/dryer	0.20	1 × 41,800 sat. steam @ 341 °F for sludge drying and house-keeping.	Fully operational. Option to sell some of the sludge as soil conditioner or to transfer some of the sludge to adjacent composting plant.	O

Note: Fuerstenfeldbruck is actually a hybrid plant because it features both two thin fil evaporators and one grinder/dryer. The evaporator capcacity is substantially larger and, therefore, this plant is classified as of the ID-SF type.

* See notes at bottom of Table III-7.

Table III-9. *European codisposal incinerators of the DD-GF type.*

Plant	Start-up	Technology Origin	Design Processing Capacities: Refuse Processing Lines	Design Processing Capacities: Refuse Plant Disposal Capacity	Design Processing Capacities: Sludge Processing Lines	Sludge to Refuse Ratio	Energy Recovery	Remarks	Operational Status (7)
Name; Country	Year (1)*	Vendor	stph (2)	STPD (3)	stph @ % TS (4)	stph/stph (5)	Lb/hr and MW(6)		
Aathus-N, DK	1977	Brunn & Sorensen	2 × 8.36	400	2 × 1.86@20	0.06	Latent heat of vaporization for sludge drying. HP hot water for district heating.	Dried sludge @ 70% TS is either burnt on grate or sold as fertilizer	O
Alloca, UK	1973	Lurgi (MHF)	1 × 4.07	98	1 × 5.29@10	0.17	RDF used for sludge drying.	Closed. Problems similar to Reigate.	NO
Altringham, UK	N.A.	Heenan-Nichols	2 × 5.0	238	2 × 2.27@5	0.03	Only latent heat of vaporization for sludge drying.	Spraying of sludge in jet from furnace wall not successful, discontinued in 1974. Also institutional problems interfered.	NO
Amager, DK (Copenhagen)	1970	Volund	3 × 13.2	950	3 × 0.46@26	0.01	Hot water for district heating, sludge drying.	Sludge codisposal practice was only added in recent years.	O
Arles, F	1977	Martin	1 × 3.33	80	1 × 0.30@30	0.04	Hot flue gases used for sludge drying. No energy export.	Sludge burning since 1978.	O
Bielefeld, G	1981	Widmer & Ernst	3 × 17.6	1,270	1 × 11.0@40 (ball mill)	0.11	3 × 11,500 lb/hr steam @ 750°F @600 psig for district heating and electrical power generation (1 × 20.4 = 20.4).	Fully operational. Unexpected boiler required major modifications.	O

* See notes at bottom of Table III-7.

Table III-9. *European codisposal incinerators of the DD-GF type. (Continued)*

Plant	Start-up	Technology Origin	Design Processing Capacities				Energy Recovery	Remarks	Operational Status (7)
			Refuse Processing Lines	Refuse Plant Disposal Capacity	Sludge Processing Lines	Sludge to Refuse Ratio			
Name; Country	Year (1)*	Vendor	stph (2)	STPD (3)	stph @ % TS (4)	stph/stph (5)	Lb/hr and MW(6)		
Bulach, CH Lurgi(MHF)	1969	Buhler/	2 × 4.07	195	2 × 6.27@3	0.16	Only latent heat of vaporization during sludge drying. RDF used for sludge drying.	In conjunction with Buhler front-end system. Shutdown in 1975 because of odor problems.	NO
Denain, F	1977	Martin	2 × 5.5	265	N.A.	N.A.	None at present but equipped for sludge drying.	Sewage treatment plant not built as intended.	NO
Dordrecht, H	1972	Martin/ Lurgi (MHF)	3 × 7.70	554	1 × 4.28@18	0.044	A portion of hot flue gases from refuse incinerator are used for sludge drying in separate MHF. Retrofit for district heating planned.	Actual sludge burning takes place on MHF. From there flue gases and fumes join those from refuse processing to pass into a common APC system.	O
Dubendorf, CH	1965	Buhler/ Nichols	2 × 4.07	195	N.A.	N.A.	Only latent heat of vaporization during sludge drying, requires supplemental firing of waste oil.	Frequent mechnical breakdowns, 1974 still working. In conjunction with Buhler front-end system	NO

* See notes at bottom of Table III-7.

Table III-9. *European codisposal incinerators of the DD-GF type. (Continued)*

Plant	Start-up	Technology Origin	Design Processing Capacities: Refuse Processing Lines	Design Processing Capacities: Refuse Plant Disposal Capacity	Design Processing Capacities: Sludge Processing Lines	Sludge to Refuse Ratio	Energy Recovery	Remarks	Operational Status (7)
Name; Country	Year (1)*	Vendor	stph (2)	STPD (3)	stph @ % TS (4)	stph/stph (5)	Lb/hr and MW(6)		
Ebingen	1962	Lurgi (MHF)	1 × 1.10	26	1 × 1.32@24	0.384	RDF used for sludge drying.	Apparently shutdown, not listed in handbook.	NO
Geneva, CH (Cheneviers)	1978	Martin	1 × 21.1	507	1 × 1.83@45	0.05	1 × 119,000 lb/hr steam for electrical power generation @455 psig & 700°F.	In operation for several years, including sludge disposal mode. The The two older and smaller units furnished by Von Roll are no longer used for codisposal.	O
Genthofte, DK	1931	Volund	2 × 6.6	320	2 × 1.59@32.7	0.13	2 × 16,500 lb/hr steam @ 206 psig & 662°F for district heating and electrical power generation (1 × 1.2 = 1.2).	Successful codisposal test program during 1974. Incinerator shutdown in 1975 due to old age after 43 years of service.	NO
Goeppingen, G	1975	VKW	2 × 13.2	634	2 × 0.41@35	0.014	2 × 70,400 lb/hr steam for cogeneration @ 573 psig & 770°F.	Sludge codisposal only on a trial basis.	O

* See notes at bottom of Table III-7.

Table III-9. *European codisposal incinerators of the DD-GF type. (Continued)*

Plant	Start-up	Technology Origin	Design Processing Capacities: Refuse Processing Lines	Design Processing Capacities: Refuse Plant Disposal Capacity	Design Processing Capacities: Sludge Processing Lines	Design Processing Capacities: Sludge to Refuse Ratio	Energy Recovery	Remarks	Operational Status (7)
Name; Country	Year (1)*	Vendor	stph (2)	STPD (3)	stph @ % TS (4)	stph/stph (5)	Lb/hr and MW(6)		
Hamburg-I,G	1963	Von Roll	1 × 8.8	210	1 × 1.10@40	0.13	1 × 28,600 lb/hr steam for cogeneration @ 580 psig & 664 °F.	Test program during 1978 to verify planning for Bielefeld, application of ball mill for homogenization of refuse & sludge. Ball mill too small, grate run at half load.	NO
Hamburg-I,G	1967	Martin	1 × 13.2	320	1 × 1.10@40	0.09	1 × 59,600 lb/hr steam for cogeneration @ 508 psig & 664 °F.	Same as above.	NO
Havant, UK	1974	Clarke Chapman & Volund	1 × 15.6	375	1 × 4.72@7.5	0.03	Hot flue gases used for sludge drying.	Only tests were performed. Some problems with spray nozzles, also institutional constraints interfered.	NO
Horsens, DK	1973/79	Bruun & Sorensen	2 × 5.5	264	1 × 5.5@20	0.13	Hot flue gases used for district heating with LP hot water.	Dried sludge is either burnt on grate or sold as fertilizer.	O
Lisieux, F	1973	Von Roll/ INDR S.A.	1 × 3.85	92	1 × 1.32@22	0.10	Hot flue gases used for sludge drying & preheating of combustion air.	Some of the dried material is not incinerated but used as a soil conditioner.	O

* See notes at bottom of Table III-7.

Table III-9. European codisposal incinerators of the DD-GF type. (Continued)

			Design Processing Capacities						
Plant	Start-up	Technology Origin	Refuse Processing Lines	Refuse Plant Disposal Capacity	Sludge Processing Lines	Sludge to Refuse Ratio	Energy Recovery	Remarks	Operational Status (7)
Name; Country	Year (1)*	Vendor	stph (2)	STPD (3)	stph @ % TS (4)	stph/stph (5)	Lb/hr and MW(6)		
Lovsta, S	1938/65	Landsverk/ Volund/ Torkap-parater	4 × 8.25 1 × 13.75	1,122	2 × 9.9@4.5	0.03	Hot flue gases used for sludge drying.	Incinerator still working but sludge processing stopped because of air pollution problems. New heat recovery for drying recycled waste paper.	NO
Lulea, S	1967	Landsverk/ Volung/ Torkap-parater	2 × 5.50	264	2 × 8.25@7.0	0.14	Hot flue gases used for sludge drying.	Original plant closed down, modification being planned.	NO
Marktober-dorf, G	1974	Dr. Pauli/ Lurgi (MHF)	1 × 2.2	53	1 × 1.10@23	0.157	Latent heat of vaporiza-during sludge drying.	Operation in 1980.	O
Niederzuwil, CH	1968	Buhler/ Nichols (MHF)	1 × 3.67	88	1.14@6	0.024	Only latent heat of vaporization during sludge drying.	In conjunction with Buhler frontend system	NO
Olten, CH	1964/70	OFAG/ Steinmuller	1 × 3.3	185	1 × 4.4@25	0.19	Flue gas provides latent heat of vaporization for sludge drying in rotary kiln.	Incineration of co-disposal composting residues since 1964. Sludge incineration started in 1970.	O

* See notes at bottom of Table III-7.

Table III-9. *European codisposal incinerators of the DD-SF type. (Continued)*

			Design Processing Capacities						
Plant	Start-up	Technology Origin	Refuse Processing Lines	Refuse Plant Disposal Capacity	Sludge Processing Lines	Sludge to Refuse Ratio	Energy Recovery	Remarks	Operational Status (7)
Name; Country	Year (1)*	Vendor	stph (2)	STPD (3)	stph @ % TS (4)	stph/stph (5)	Lb/hr and MW(6)		
Reigate, UK	1973	Lurgi (MHF)	1 × 4.07	98	1 × 5.26@8	0.20	Only latent heat of vaporization during sludge drying.	Refractory problems, heat flow control problems. Similar to Bulach CH. Closed mainly because of institutional problems.	NO
Valenciennes, F	1977	Martin	3 × 5.55	400	N.A.	N.A.	None at present but equipped for sludge processing.	Sewage treatment plant not built as intended.	NO
Oftringen, CH (Wiggertal)	1974	OFAC	2 × 4.58	220	2 × 3.30@25	0.24	Hot flue gases used for drying sludge cake in rotary kiln.	Incinerator and WWTP are located on the same property. Sludge incineration since 1975.	O
Wistom, P	1975	Lurgi (MH)	1 × 1.43	34	1 × 4.62@40	1.72	Hot flue gases used for sludge drying.		O
Wurzburg, G	1984	Martin	2 × 13.6	660	2 × 3.96@40	0.15	2 × 62,300 lb/hr steam @ 585 psig & 780°F for district heating and electrical power generation (1 × 11.5 = 11.5).	Construction complete, testing in progress.	O

* See notes at bottom of Table III-7.

Table III-10. *European codisposal incinerators of the ID-CF type.*

			Design Processing Capacities						
Plant	Start-up	Technology Origin	Refuse Processing Lines	Refuse Plant Disposal Capacity	Sludge Processing Lines	Sludge to Refuse Ratio	Energy Recovery	Remarks	Operational Status (7)
Name; Country	Year (1)*	Vendor	stph (2)	STPD (3)	stph @ % TS (4)	stph/stph (5)	Lb/hr and MW(6)		
Antwerp, B	1980/83	Seghers Eng.	2 × 8.8	420	2 × 1.14@85 to incinerator 1 × 2.82@50 to dryer	0.11	Thermal oil heat exchanger to provide latent heat for sludge dryers.	Refuse incineration started in 1980, but wastewater treatment plant initially only test runs with imported dryers. Was completed later in 1982.	O
Brive, F	1973/75/81	Von Roll/INOR S.A.	3 × 3.85	277	3 × 2.75@11	0.11	3 × 21,300 steam @ 152 psig & 379 °F for sludge drying. Future heating of greenhouse planned.	Refuse incineration started in 1973, sludge incineration 2 years later (Luwa thin film dryer).	O
Deauville, F	1976	Von Roll/INOR S.A.	2 × 2.75	132	1 × 0.99@8	0.02	2 × 16,500 steam @ 217 psig & 180 °F for sludge drying.	Luwa thin film dryers with 55-60% TS concentration at outlet.	O
Dieppe, F	1974	Von Roll/INOR S.A.	2 × 3.30	158	2 × 0.83@57.5	0.19	2 × 16,500 steam @ 217 psig & 180 °F for sludge drying.	Luwa thin film dryers with 55-60% TS concentration at outlet.	O

* See notes at bottom of Table III-7.

having 260 × 100 mm holes to a conveyor belt. From here the scrap is magnetically separated before the waste is stored in an intermediate bunker (2,300 m^3) and then it is transported to the hoppers for incineration. Results so far indicate that steam production varies only by about plus or minus 2 percent, the heavy metal content of the flue gas is only about 10 percent of known usual figures, and the incineration of the shredded and mixed waste on the grates is problem free. From this viewpoint, the additional investment for the mill (4 percent of the total investment or about 5 million DM or $2 million) seems to be justified. One major problem to date has been the unexpectedly large amounts of malodorous off-gases from the mill house. This will be rectified by directing this polluted air through the secondary air supply system of the incinerator.

An interesting approach to the incineration of household waste and sewage sludge is scheduled to start in the near future. In 1975, two mass-fired household waste incinerators went into operation with capacities of 12 tons/hr each, with space for a third unit of the same capacity. With an increasingly difficult sewage sludge disposal problem, the Federal Government decided in 1982 to add to the existing incinerator a mixing and homogenization device to coincinerate the sludge. The plan includes installation of a rotary kiln with a length of 32.5 m (107 ft) and an inner diameter of 5.0 m (16.5 ft). Unshredded household waste and sewage sludge (500 tons/day of waste and 100 tons/day of sludge with a solids content of about 35 percent) will be fed into the kiln, which will rotate at 0.8-4 rpm. The kiln will be indirectly heated with steam from the incinerator. During its residence time of about 8 hours, the charge will be mixed, partially ground (from heavy components in the waste), homogenized, and dried. The off-gases from the kiln will be drawn out of the kiln with hot air and discharged into the incinerator as secondary air, the mixed charge being subsequently fed onto the grates of the incinerator. The retrofitted plant will cost an additional 10 million DM ($4 million). The concept of retrofitting existing incinerators (provided they are state of the art with respect to flue gas cleaning), enabling them to coincinerate mechanically dewatered sewage sludge together with household waste, makes this solution an interesting one.

The coincineration plant at Marktoberdorf was built in 1973 and went into operation in 1974. Approximately 2 tons/hr of municipal waste are incinerated in a mass-burning incinerator with a grate system. In the adjacent multiple-hearth incinerator, approximately 1 ton/hr of undigested sewage sludge (about 80 percent water content) is incinerated after dewatering in a centrifuge. The heat of a portion of the flue gases from the grate incinerator at 800° - 1,000°C is used in a counterflow manner to dry the sludge in the upper hearths of the sludge incinerator. The odorous flue gases (250° - 350°C) are recycled into the waste incinerator for complete combustion. The balance of the flue gases from the waste incinerator enter a scrubbing system to eliminate dust and noxious gases before they are released into the atmosphere. In Marktoberdorf there is no heat recovery apart from the support of sludge incineration. The overall investment costs have been about 5.5 million DM ($2.2 million).

At Dordrecht, Holland, a combined system for refuse incineration, sewage treatment, and drying and incineration of sludge has been in operation for more than 10 years and has worked well. The combination results in a minimum of residues, as the sludge is converted to ash. Scrubber water is taken from the sewage treatment plant effluent and recycled back for treatment. Data are provided on the effectiveness of the flue gas washing in removal of HCl, HF, SO_2, and dust. The sludge incineration flowsheet (Figure III-3) is presented in terms of fates of six heavy metals. Compounds of cadmium, lead, and zinc are volatilized into the flue gases; chrome, copper, and nickel are found in the ash from the sludge. The Dordrecht wastewater treatment plant is one of the rare examples in the Netherlands of a combined installation for the treatment of refuse, sewage, and sludge. The sludge is dewatered, dried, and incinerated; dewatering is achieved by means of a centrifuge; and drying, and incineration is by a MHF.

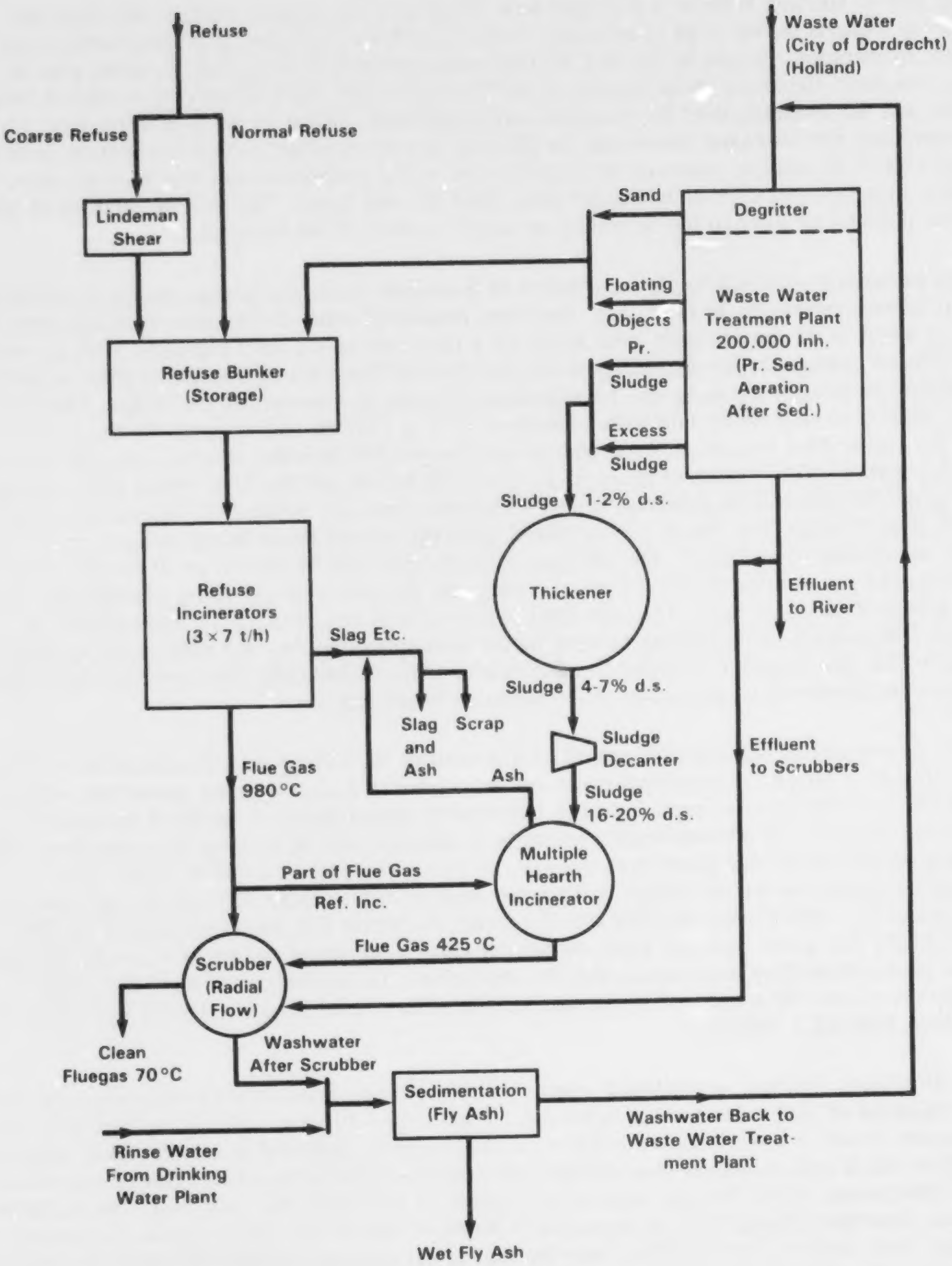

Refuse
Coarse Refuse
Normal Refuse
Lindeman Shear
Refuse Bunker (Storage)
Refuse Incinerators (3 × 7 t/h)
Slag Etc.
Slag and Ash
Scrap
Ash
Flue Gas 980°C
Part of Flue Gas Ref. Inc.
Flue Gas 425°C
Scrubber (Radial Flow)
Clean Fluegas 70°C
Washwater After Scrubber
Rinse Water From Drinking Water Plant
Sedimentation (Fly Ash)
Wet Fly Ash
Washwater Back to Waste Water Treatment Plant
Waste Water (City of Dordrecht) (Holland)
Degritter
Sand
Floating Objects
Pr. Sludge
Excess Sludge
Waste Water Treatment Plant 200.000 Inh. (Pr. Sed. Aeration After Sed.)
Sludge 1-2% d.s.
Thickener
Sludge 4-7% d.s.
Sludge Decanter
Sludge 16-20% d.s.
Multiple Hearth Incinerator
Effluent to River
Effluent to Scrubbers

Figure III-3. Flow sheet of the Dordrecht installation.

In the early 1960s, when the domestic refuse incineration plant built in 1938 started to show signs of wear after 25 years of service, plans were begun to build a new installation. Because of the absence of a sewage treatment plant in Dordrecht, all sewage was discharged directly into the Rhine River. This situation was no longer acceptable, and a combined refuse and sludge treatment plant was planned. The refuse processing was to be achieved by means of incineration, and the combination refuse-sludge treatment was to be technically and economically viable. Because it was virtually impossible to find or create a market for digested sludge in the region surrounding Dordrecht, the sludge also was to be incinerated. Flue gases were to be cleaned to meet government regulations covering dust and hydrogen chloride (mostly from PVC). Some attention was to be given to the recovery of heat; but since the first oil crisis had not yet occurred, no emphasis was placed on this feature. The necessary equipment for each stage of the process was to be sufficiently tested and available from reliable companies.

An investigation into the combined composting of refuse and undigested sludge showed that this was technically possible. However, this method presented problems in relation to shredding and the iron content in the refuse. Also, the removal of organic and inorganic components that could not be composted was a problem. The largest drawback, however, was that no stable market could be found for the compost end product. An investigation showed that thermal sludge conditioning was not attractive because of the increased load on the sewage treatment plant. Of all the oxidation processes, neither the pyrolysis method nor the fluidized-bed one was commercially available at the time; only the multiple-hearth incinerator, as used in the roasting of ores, could seriously be considered. Using this method, only the inorganic substances of the sludge either remain as ash or are entrained in flue gases. It was necessary to dewater the sludge to 15-20 percent dry solids, and auxiliary heat had to be provided in a MHF for the incineration of sludge. The combined incineration of domestic refuse and sludge as practiced in Ebingen and Bulach, demanded the removal of any iron and the shredding of the refuse prior to the mixing of refuse and sludge because of the high rate of mechanical wear in the mixers and in the furnaces. With an improperly controlled process or too low a caloric value in the refuse, the temperature in the upper part of the incinerator would be lowered. As a result, incomplete incineration and pyrolysis would occur and thus cause odor problems. This has already occurred at the Bulach installation, which had to be closed down for that reason.

The combined incineration in grate-type incinerators without prior shredding and mixing of refuse and sludge leads to the formation of balls of sludge that are carbonized on the outside but unburned on the inside. These give odor problems at the disposal site. Spraying of sludge on refuse causes objections on hygienic grounds. When it was shown that the solid waste incineration capacity had to be enlarged to accommodate the sludge contribution, it was concluded that the building of a special sludge incinerator next to the three planned refuse incinerators was the best solution. Figure III-3 shows the flowsheet of the installation. The temperature of the flue gases from the refuse incinerators is 900° - 1,000°C. The sewage treatment plant has a degritter, primary sedimentation, aeration, and secondary sedimentation basins. The waste-activated sludge from the secondary sedimentation is mixed with the inflowing sewage. The sludge from the primary sedimentation is collected in a thickener. The thickened sludge is further dewatered by a centrifuge and subsequently discharged into the sludge incinerator. The flue gas from one of the three refuse incinerators (capacity 7-1/2 tons/hr) is led into the sludge incinerator countercurrent to the sludge, as a result of which drying and incineration of the sludge occurs. The ash from the sludge incinerator is moistened in a mixer (Eirich-type) to reduce dust and then discharged into containers for disposal. Some development work has been done to find possible applications for the slag that is produced. Some experimental paving stones of good quality have been produced, using up to 1 kg of slag per 3 kg paving. Slag might also be used as a road foundation material.

In conclusion, there are several advantages of the Dordrecht integrated system for refuse and sewage sludge incineration. Residues are minimal and it is possible to wash the flue gas with WWTP effluent. Substances such as HCl and HF are washed out at the same time as dust. The rise of the treatment plant's water temperature results in improved sedimentation and (de)nitrification.

COMPARATIVE EVALUATION OF SEVEN EUROPEAN COCOMBUSTION SITES

Between June 26 and July 8, 1982, seven Western European mass-burning facilities that coincinerate wastewater sludge with solid waste at various ratios were visited and evaluated for comparison purposes. The facilities varied in size from 72 to 860 Mg/d (80-950 tons/day). Energy in the form of steam or hot water was recovered by three plants for district heating, by three plants for generation of electricity, by four plants for drying of sludge prior to combustion, by one plant for thermal conditioning of sludge in an adjacent facility, and by one plant to maintain set temperatures in standby furnaces not presently in operation. Only one plant did not recover some energy in a boiler. All energy recovered at this plant was used, as hot flue gas, to dry sludge in a dryer. All plants having boilers also had furnaces of water-wall construction, as opposed to the refractory-wall construction of the plant without boilers.

Regarding sludge processing, two plants received sludge in the refuse pit, where it was mixed with refuse prior to charging. One plant received sludge cake into a pit, then transported it to a "slinger," a device very similar to those used to ballistically project pulverized coal onto a traveling grate in a semisuspension furnace. The slinger-type feeder disintegrates sludge (at about 45 percent solids) into particles of slightly varying sizes and distributes it uniformly over the burning refuse layer.

One plant dried the sludge, prior to combustion, in a thin-film, steam jacket dryer. Another plant dried the sludge, prior to combustion, in a rotary kiln, flue gas dryer, with no dried sludge or off-gas vapor recycling. Two plants dried sludge, prior to combustion, in mill-type, flue gas dryers, with dried sludge recycling (to prevent formation of sludge balls from too wet a sludge entering the dryer) and with off-gas vapor recycling (to lower the dryer operating temperature, thereby preventing explosions and fires).

The sludge to solid waste ratio as received at the facilities varied between 1:6 and 1:22 for facilities receiving dewatered sludge, with a value of 1:5.5 for Deauville (France), which received liquid sludge. The combined moisture content of the sludge and refuse handled at the seven facilities ranged from 25 to 32 percent. On the basis of the heat balance, all the facilities visited operated at a ratio of average Btu's released to Btu's required to vaporize the moisture, which was in excess of 4.9:1.

Applicability of European Technology to the United States

Recently, many municipalities in the United States have become interested in the feasibility of coincineration of sludge and solid waste. While a limited number of U.S. municipalities have conducted studies or experimented with coincineration, little long-term operating experience exists. As of 1984, only two municipalities out of four with coincinerating facilities in the United States—Stamford, CT, and Glen Cove, NY—are currently coincinerating sludge and solid waste.

In Western Europe, the high cost of oil and shortage of open land have frequently made coincineration an economically attractive method for disposing of waste products. As a result, a number of municipalities in Western Europe have practiced coincineration for many years. Based on the 1982 visit to seven facilities to compare their technological approaches to coincineration and evaluate the applicability of their technologies to sludge and solid waste disposal in the United States, the following comments can be made:

- The heating value of solid waste in the United States is generally higher than in Europe. This means that, on the basis of the heat available from a given amount of solid waste, the ratio of the amount of sludge that can be coincinerated with solid waste should be higher in the United States.

- With regard to air pollution control standards, Germany has the most stringent standards of the countries visited. Bamberg used wet scrubbers in conjunction with electrostatic precipitators. Goppingen was in the process of installing dry scrubbers ahead of their electrostatic precipitators. This level of air emission control is comparable to the most stringent level imposed by some states in the United States.

- In Europe, most of the coincineration facilities are owned and often operated by the municipality. In the United States, there is a trend towards full-service contracts for solid waste, mass-burning facilities with energy recovery. In the full-service approach, the full-service vendor must assume the risk for any problem associated with coincineration. Since the introduction of sludge to a mass-burning furnace may increase maintenance costs and reduce potential vendor profits from the sale of energy, most full-service vendors in the United States look with disfavor upon coincineration. The full-service approach, therefore, may not be the best procurement method for implementing coincineration in the United States.

- In Europe, the level of staffing observed at the coincineration facilities appeared significantly higher than what one typically sees at U.S. mass-burning facilities. It appears that the Western European people are willing to assume higher costs for what they perceive to be a superior method for waste disposal in terms of environmental considerations.

- All of the plants visited were originally designed for burning refuse alone and were later retrofitted with equipment to allow incineration of sludge. As a result, sludge storage and processing units were often scattered all over the building, which in some cases necessitated lengthy sludge cake conveyance systems. These problems will presumably be eliminated when new systems are designed as coincineration facilities rather than retrofits.

The Future of Cocombustion

The stabilization of energy costs in the past few years has resulted in an abatement of the rush to utilize refuse as an energy source, with time to reflect on the negative aspects of its use. For example, it was previously assumed that RDF could be prepared on a routine basis. However, actual experience with explosions, fires, and other hazards has resulted in a more realistic appraisal and diminished the interest in grinding and classifying refuse to make a fuel for addition to a sludge furnace.

There could be a renewal of interest, particularly if the cost of landfilling rises to the levels of the ''true'' cost to process refuse in technically sophisticated ways. Also, although cheap, close-in landfill space that can be used with minimum political complications has been used up, there is plenty of land available if the transportation costs can be met and if higher levels of government declare that such use is the ''highest and best use,'' as they have done in cases of toxic waste disposal. Further, it is possible that regional waste disposal districts could be created and given responsibility for ultimate disposal of both refuse and wastewater solids. Such a regional agency could apply sound engineering and economic analysis to arrive at the most environmentally sound yet cost-effective methods.

In such an integrated disposal program, it must be recognized that any method of thermal conversion would still result in some type of residual that must find an ultimate resting place. In cocombustion based on preparing RDF, there are inert residuals from the RDF-making system and from the combustion system, so the adoption of these systems is not a total solution; landfill space of some magnitude must still be provided.

In virtually every successful case of cocombustion, the prime combustor has been a refuse-type furnace. Past efforts to utilize furnaces designed for sludge to burn refuse also have been less than successful. If it is assumed that a sludge furnace must be used, there is reason to believe that the fluidized-bed combustor would be more appropriate for the addition of chopped refuse than would the multiple-hearth design; however, only scattered results are available for proof. The wet-milling process applied to refuse at Franklin, OH, evidently produced technical success for several years, after the FBF was modified. At Duluth, MN, the FBF design could not be altered sufficiently during the startup period to permit stable operation with RDF containing substantial inert matter, although another design was suggested that could overcome the problems experienced there.

As of 1984, there is no implementation of the starved-air combustion of mixed sludge solids and highly prepared refuse that was demonstrated in pilot tests by manufacturers of MHFs in New Jersey and California in the mid-1970s. Both of these manufacturers have gone out of business in the past few years, as have several other major companies that competed in the municipal market in the past decade.

In summary, without a strongly motivated industry trying to sell engineered products, without financial incentives such as construction grants or attractive loans, and without a fear of energy supply shortage, it seems unlikely that there will be any active development of cocombustion in the United States in the near future.

CHAPTER IV. THE MANAGEMENT OF AIR EMISSIONS, ASH, AND OTHER RESIDUALS

INTRODUCTION

The combustion of waste matter results in the production of two major types of residuals—gaseous and solid. After scrubbing, the gaseous stream is dispersed into the atmosphere. The solid stream, which consists of ash material, must be placed in an ultimate disposal site such as a landfill. This chapter will discuss the present regulatory situation regarding each and the process considerations that govern efforts toward compliance.

Various forms of solid matter or residuals result from wastewater treatment and may be processed at the plant site before they are transported to ultimate disposal. Although the major consideration in this chapter is ash produced during sludge incineration, it is appropriate to review all types of material removed in treating wastewater. These can include: interceptor debris, screenings, grit, primary settling tank scum, primary sludge, biological treatment sludge, chemical treatment sludge, final settling tank scum, sand filter backwash, and solids from cleanup and maintenance. Each of these can carry pathogenic organisms along with organic material, create an odor nuisance, and be combusted. Most commonly only primary and biological sludges and scum are incinerated. In plants that use inorganic chemical conditioning of sludge before dewatering, the chemicals, such as lime and ferric chloride, remain with and add to the ash requiring disposal. There are three main topics in this review of residuals management: (1) handling of the ash and/or other residuals, (2) environmental risks in ultimate disposal, and (3) utilization instead of disposal.

NATURE OF THE CHALLENGE

About 4 million dry tons of sludge are generated in U.S. municipal wastewater plants each year. Over a million tons of this are incinerated resulting in about 400,000 tons of ash that must finally be placed in an environmentally compatible manner.

Handling of Ash in the Plant

Ash that is slurried as it leaves the furnace creates occasional problems within the vicinity of the furnace, such as rapid wear on pumping equipment and piping, plug-ups at bends or restrictions, and high humidity and corrosion above the slurry tank. However, there are not the dust and abrasion problems that can occur in dry ash handling systems. Dry ash handling, which applies principally to MHFs, is best when the ultimate disposal site is remote from the plant and when a time lag may occur between generation and shipping. Wet ash handling is most likely to be chosen when a lagooning site is available on or near the plant property. Over a long span of time, it is probable that ash stored in this way will have to be moved elsewhere by truck, and this later cleanout and disposal cost should be factored into any economic analysis. Another element of concern in wet ash lagooning or final deposit is that the leaching process will start right away, and if a valuable aquifer could be impacted, higher cost lining may be demanded. Wet ash handling is essentially the only method for a fluidized-bed system because all of the ash is blown out of the combustor and caught in the scrubber. The result is a fairly low ash concentration compared to the slurry from an MHF wet system. The FBF ash slurry is usually thickened in a tank and may also be dewatered on a filter before it is shipped to disposal. Ash can usually be handled by standard earth-moving equipment at the landfill site or in the lagoon cleanout process.

Environmental Risks in Ultimate Disposal of Ash

Municipal sludge ash is normally exempted from regulation as a solid waste. As a result, municipal sludge ash can usually be landfilled at a sanitary landfill, unless local or state regulations deem otherwise. Actually, many tons have been placed over the years without any credible evidence of hazard to the public or environmental effect. The Resource Conservation and Recovery Act of May 1980 specifies leachability standards for substances and can result in a toxic waste rating for the ash. For example, if there is a tannery in the area, the hexavalent chromium can result in a test leachate exceeding the 5 mg/l limit. This is the exception rather than the rule, but the problem can arise, and ash must be checked for compliance.

Landfill is normally the least costly method of ultimate disposal. If the cost becomes too high, other alternatives may be considered attractive. The same applies if a toxic rating is given to an ash. In the following discussion on the utilization of ash, the methods will be classified in three groups: (1) what is presently being done, (2) what has been tested, and (3) what can be done.

Utilization of Ash

Ash is a valuable resource in that its phosphorus has been shown capable of increasing crop yields. Often the ash contains free lime, which is a beneficial soil additive in many locations. Ash can also be used as a filler in asphalt road mix. Here the ash serves as the fine material that fills the small voids among the pieces of gravel and increases the strength of the material. This also leaves a smaller void for water penetration and helps prevent freezeout in the winter. Another use of ash is in building products, if the product color is not a problem. Although the iron will often color a concrete or cinder block a dull red, the ash will act as a filler that allows the formation of sharp corners in the cinder blocks and concrete blocks.

Ash has been used as a sludge filter aid for many years at Indianapolis' Belmont Sewage Treatment Plant, but the added cost of erosion and other maintenance is high. Although this practice does not eliminate ash, it saves operating labor and may eliminate filter-room odor problems that lime causes. A polymer-conditioned biological sludge cake that is "sticky" releases more easily from the filter fabric if ash is added. The negative aspect is that the adherent moisture adds [illegible] heat requirement in incineration and reduces furnace capacity for sludge solids. Ash also [illegible] to migrate throughout the plant's processes, because filtrate and belt washwater is recycled upstr[illegible]

Ash can be used within the plant area to promote the growth of grass or other cover; it can be spread to 15 cm (6 in) or more of depth and will not wash away. Grass planted in this ash cover will grow and stabilize the area. If ash is used for these purposes, then the problem of no-vegetation growth can become one of overvegetation and additional maintenance may be required to keep the grass cut.

Another use for sludge ash that has been tested but is not in widespread use is the chemical fixation process. This process converts some wastes into nontoxic, nonpolluting material suitable for landfill. This type of process often uses the lowest cost material that is locally available as part of the process material. However, the process is not a big user of ash at the present time.

As chemical fertilizer manufacturers are well aware, ash can contribute to the quality of their product. In a complex fertilizer plant, it is often necessary to add a filler to achieve the right concentrations of fertilizer. Sand is often used for this purpose because it is convenient. When ash is used for this purpose, it must be completely burned out because any organics mixed with a nitrate mixture can start a fire if the mixture gets too warm.

A process that eliminates the disposal of ash after incineration is the use of sludge as fuel in the manufacture of Portland cement. Dried sludge has been substituted for peat or low-heat value coal used in the cement kilns and leaves no ash. One location using this process had no problems, while another had a smoke problem. However, the second location was a demonstration project with the equipment set up temporarily for that purpose.

Using sludge to make bricks can also eliminate the ash disposal problem. It is possible to make bricks that substitute up to 30 percent sludge for the clay. The bricks resulting from this are described as common bricks and have a better bonding to mortar than do all-clay bricks. Since sawdust was formerly used in fire-brick products, it may also be possible to use sludge as a part of fire bricks or ''refractory'' products. It is also possible to use ash itself in bricks.

In the future, there may be other methods for eliminating sludge ash. In 1973, for example, approximately 1.28 million tons of slag were used in this country to produce mineral insulating wool. Sixty percent of this was blast furnace slag. To make mineral insulation, industry uses water-cooled, cokefired furnaces that melt the slag and produce the fibers. Since a good deal more insulation is produced now than in 1973, it seems that a lot of sludge ash could be converted into insulation. Mineral insulation is a black, pressed-block type of insulation. Although it is primarily used for industrial insulation, it also comes in sizes that can be used for house insulation.

The ''flying saucer process'' can convert ash into a usable construction material. It has been done for fly ash and could also be done for sludge ash. In this process, which is used for upgrading phosphate rock or iron ore to electric or blast furnace quality, the material is formed into balls on a rotating disc. The disc is set at an angle, and then ash is fed onto it. As the disc rotates (thus, the ''flying saucer'' name), small amounts of water are sprayed onto the ash and a few particles of ash stick together and start rolling. As the disc turns, more particles of ash stick together forming a larger particle that rolls and sticks to other particles. As the disc continues to turn, the particles agglomerate sufficient material to form a ball. The diameter can vary from marble- to teacup-size balls. Once the balls are large enough, they roll over the lip of the disc and go to a sintering furnace. After sintering, they have enough strength to pass through an electric furnace or blast furnace without fracturing. This strength is sufficient for the material to be used for construction purposes.

Another method that has not yet been tried in the United States is using ash as a growth promoter on field crops. Soviet scientists have substantially increased the growth of radishes, potatoes, and beets by using this method. In Japan, as noted previously, ash is sold as a fertilizer. Phosphorus is a well-known promoter of healthy root growth. It is believed by some that the iron that is magnetized slows down the growth of soil bacteria that consume nitrogen, leaving more nutrient for the plants. Also, some bacteria beneficial to the plants grow better in the magnetic field created by the iron.

It would be ideal to be able to sell all the ash for other uses. Analysis of the ash might find something of value that would make it saleable. For example, the city of Palo Alto, CA, found 32 ppm of gold in its ash (a legacy of Silicon Valley electronics manufacturing) and was able to sell it. At that time 3.2 ppm of gold in natural ore was considered high enough for profitable recovery.

The expression ''all that glitters is not gold'' can also be applied to ash in reverse. In Japan, blast furnace slag is blended with aluminum hydroxide sludge, and the resultant mixture is used for jewelry and artificial marble. Since jewelry and artificial marble can be made by adding silica, soda ash, and other blast furnace slag materials, why not substitute the ash from sludge? The color, hardness, and other features of the products could be changed by the types of additives used and the method of processing.

AIR EMISSIONS CONTROL

Current United States Requirements

The air emissions standards applicable to new designs for sludge incinerators in the United States include:

- Particulate emission—expressed as pounds per ton or in grams per kilogram dry feed (The new source performance standard is 0.65 g/kg.)
- Opacity—expressed as a percent of total opaqueness (The standard is 20 percent; some states limit this to several minutes per hour.)
- Beryllium—expressed in grams per 24 hours from entire site (The standard is 10 g and is rarely a concern.)
- Mercury—expressed in grams per 24 hours from entire site (The standard is 3,200 g, and is virtually never even approached.)

Commonly, the beryllium and mercury compliance is verified by analysis and mass calculation of mass in the feed, assuming that it all leaves the system in the stack gases.

Other pollutants that have been defined in local area codes include: hydrocarbons; carbonyls; partial combustion products such as aldehydes; carbon monoxide; sulfur oxides; nitrogen oxides; chlorinated organics such as PCBs and pesticides; and odor. In addition, some jurisdictions apply a minimum temperature such as 650° or 760°C (1200° or 1400°F) and retention time at that temperature in lieu of specific limits on organic constituents and odors.

Metal Emissions Control — Wet Scrubbing Systems

The general concern in the regulatory community about higher-molecular-weight metallics has given rise to investigations in Japan and the United States to determine if these species leave the incinerating system by the stack in sufficient amount to constitute a risk to the population in the vicinity of the plant, as well as to the workers. As a result, the United States Environmental Protection Agency (USEPA) has evaluated the findings from tests on nine sludge incinerators in which the following metals were determined: cadmium, iron, nickel, lead, chromium, silver, copper, manganese, zinc, and arsenic. There are currently no Federal emission standards specifically governing emissions of any of these metals from sludge incinerators. The Federal standard for ambient air lead concentration is 1,500 $\mu g/m^3$, and work under way at the Research Triangle Park Laboratory of USEPA has led to proposal of a cadmium standard of 100 $\mu g/m^3$. Of concern to the investigators was the finding that both lead and cadmium seemed to be fugitive, passing through the existing low-energy scrubbing systems. This presence was presumably in the form of submicron particles created by vaporization in reducing conditions in the combustion zone and later condensation of the metals. However, the median ground level concentration increment was computed to be very small. The findings of this recent investigation, reported in 1981 but not yet published, restated the findings of an earlier USEPA task force that had concluded in 1972 (EPA-R2-72-040) that "properly operated incinerators produce acceptable stack emissions of particulate matter, nitrogen oxide, sulfur oxides, and odor." In this recent work, the concerns about the heavy metals were also allayed, thus permitting the statement: "The amount of heavy metals contributed to the atmosphere from incineration of municipal wastewater sludge is insignificant when compared to that already in the atmosphere and does not appear to create a threat to the environment." The conclusions of this working paper follow.

1. Five of eight sewage sludge incinerators met EPA's new source performance standards of 0.65 g of particulates per kg of dry sludge solids feed. Of the remaining three, only one significantly exceeded the standard. None of these incinerators had to meet new source performance standards when constructed, although most of them had undergone some upgrading of their particle removal devices. This is an encouraging result and indicates no extreme hardship created by the standard.

2. Overall efficiencies of the scrubbers varied widely and no correlations were evident. When efficiencies for removal of various particle-size fractions were compared, differences in overall efficiency could be explained. All scrubbers showed good removals for size fractions larger than 1.0 μm. However, efficiencies ranged from about 50 to 90 percent for the 0.1 to 1.0 μm fraction. No significant improvements in performance were evident from the use of higher pressure drops or use of a Venturi scrubber upstream from an impingement scrubber. This is not unexpected because the scrubbing systems for the plants were totally unrelated.

3. Material balances around the incinerators (not including the scrubbers) for cadmium and lead show results consistent with the other metals. These metals evidently are being collected by the particle collection apparatus as efficiently as other metals.

4. Silver and zinc are not concentrated into the particulates by the incineration process. However, those particles that are carried overhead are fine and concentrate in the fines fraction. Consequently, since the scrubbing systems are less efficient for fine particles, they are not recovered as efficiently as the bulk of the particles, and their concentration in the particle catch at the scrubber exit is substantially higher than at the inlet.

5. Cadmium and lead, probably by virtue of the chemical transformations that cause them to be concentrated into the particulate fraction leaving the incinerator, are fine and are concentrated in the fines fraction. Consequently, their concentration in the particle catch at the scrubber exit is substantially higher than at the inlet. Arsenic probably behaves in the same way as cadmium and lead.

6. The enrichment of Cd, Pb, probably As, Ag, and Zn that occurs across the scrubber is directly related to the presence of these metals in high proportion in the 0.1-1.0 μm fraction leaving the incinerator.

7. Generally over 90 percent of the Cd, Pb, probably As, Ag, and Zn that leave the scrubber as particulates are found in the 0.1 to 1.0 μm fraction.

8. The median ground level concentrations for lead, calculated from plume models, averaged 25.8 ng/m^3, which is only 2 percent of the actual ambient concentrations in the cities where the incinerators are located and 1.7 percent of EPA's standard of 1500 ng/m^3.

9. For cadmium, the median of the calculated ground level concentrations averaged 1.5 ng/m^3. This level approaches actual ground level concentrations but is only 1.0 percent of a suggested standard of 100 ng/m^3.

10. The low concentrations of lead and cadmium relative to concentrations of health significance indicate that sludge incineration creates little or no threat to health from these metals.

11. The comparable material balances of lead and cadmium when compared to other metals indicate good collection of these metals by the SASS train and its 0.1 μm filter. If desired,

use of a filter downstream from the scrubbing system would assure virtually complete collection of metals except mercury.

12. Sulfur dioxide and nitrogen oxides levels are very low compared to ambient standards and to other sources of these pollutants.

Particulate Emissions Control — Wet Scrubbing Systems

Particulate emissions from sewage sludge incineration can vary widely. The variables in the sludge that seem to determine the emissions are (1) nature of the sludge (this can vary by hour, day, or season), (2) type of incinerator, (3) temperature of incinerator operation, (4) moisture content of the sludge, (5) volatiles content of the sludge, (6) amount of excess air used for incineration, (7) sludge feed rate to the furnace, and (8) the type of particulate removal system following the incinerator. Perhaps the most important factor related to emission rate is operator knowledge of the incineration process.

The nature of the sludge varies by location. At any location, sludge varies daily, weekly, or seasonally and may change entirely over a period of a year because industrial sources can change the character of the waste they discharge to the sewer or they may discontinue operation. A meat packing plant could be an example of this. This one plant could dump hair into the system. This would improve the dewatering capability of the waste treatment plant and result in a sludge requiring a smaller amount of fuel for incineration. Paper plant wastes are another example of an industrial discharge that can make a sludge easy to dewater and burn. Emissions can be affected by the type of sludge (i.e., primary, secondary, or tertiary). As more plants produce secondary and tertiary sludges, the emissions become harder to remove by conventional water scrubbers regardless of the pressure drop across the scrubber.

The particulate emissions, prior to passing through the scrubber system, are usually highest for a fluidized-bed incinerator because the ash is removed from the furnace with the flue gas. Particulate emissions quantities from multiple hearth incinerators are variable but usually less than fluidized-bed incinerators because the ash is removed as bottom ash. Electric furnaces have the smallest amount of particulate emissions, because the sludge is not stirred or mixed during incineration.

The higher temperature of operation in a FBF results in higher levels of emissions, including heavy metals. Operation at 980 °C (1800 °F) normally produces 200 to 400 percent more emissions than operation at 760 °C (1400 °F). This increase in heavy metals could also be true for a multiple hearth incinerator.

The moisture content of the sludge and the amount of excess air in the furnace can also have an effect on emission rates. High gas velocities within the incinerator resulting from large quantities of excess air, along with steam from high moisture content sludge, are believed to increase the suspended particulate load that leaves the furnace with the flue gas. Supplemental fuel requirements are also increased by the need to evaporate moisture and to heat excess air.

The volatile content of the sludge determines the amount of supplemental fuel required for incineration. Although higher volatile content in the sludge is usually desirable, it can be a problem when combined with a low moisture sludge. This combination can cause increased emissions because the sludge will explode (burn rapidly) as it is introduced into the top hearth of a multiple hearth incinerator.

A high ash content (low volatile solids) sludge appears to reduce emissions. One waste treatment plant that had a high ash content (the ash kept wearing out the sludge processing equipment) had a low emission rate despite a malfunctioning scrubber system. Another plant that used ash as a filter aid had a low emission rate despite the use of a modified wetted wall cyclone as the only particulate removal system.

A constant sludge feed is desirable for MHF feed incineration because changes in feed rate, both up or down, can cause smoke and/or increase emissions. Neither the U.S. EPA nor any contractor, to our knowledge, has initiated studies on the relationship between operating conditions and emission rates.

Historically the efficiency of a particulate removal system has been related to pressure drop across the particulate removal equipment. Most incinerators now use a Venturi impingement tray water scrubber that develops 30 inches or greater of water pressure drop across the system.

A demonstration project was performed at Indianapolis, IN for the purpose of determining operating methods that would achieve more efficient fuel usage. The contractor who did the work for Indianapolis has also performed similar work at seven other locations, and it is believed (not documented) that air emissions were reduced at all locations.

The fuel reduction work has been documented for three of the cities and published in the following documents:

1. "Plant-Scale Demonstration of Sludge Incinerator Fuel Reduction," (Indianapolis, IN) EPA 600/2-83-083 NTIS-PB 83-259 697.

2. "Sewage Sludge Incinerator Fuel Reduction at Nashville, Tennessee," EPA 600/2-83-105 NTIS-PB 84-113 075.

3. "Sewage Sludge Incineration Fuel Reduction, Hartford, Connecticut," EPA 600-84-146 NTIS-PB 84-243 096.

These multiple hearth fuel reduction studies were accomplished by temporarily instrumenting each incinerator. Data on operating modes for the individual furnaces were collected by means of a computer program. The procedures for operating the furnaces were then used to retrain the operators, who could then use the controls and instrumentation that already existed to maintain the reduced fuel consumption and, it is assumed, reduced air emissions.

At this time the U.S. EPA does not anticipate any demonstration projects to relate furnace operating modes to particulate emissions of multiple hearth incinerators. This work should not be done until a reliable oxygen analyzer, a constant moisture determination system, and a constant sludge feed system can be added to multiple hearth incinerators. Procedures that can immediately be utilized to reduce air emissions from multiple hearth furnaces are (1) constant sludge feed rate, (2) operator training to achieve fuel efficiency, and (3) proper operation and maintenance of particulate removal equipment. It is predicted that a 25 percent reduction in supplemental fuel can be achieved at most multiple hearth sewage sludge incinerator facilities by the plant operating and maintenance staff through use of procedures in the fuel reduction documents listed above. These procedures should also reduce air emissions from the multiple hearth incinerator because less excess air will be required for incineration.

Air Emissions Control — Dry Scrubbing Systems

The Hyperion Energy Recovery System (HERS), as described in Chapter V, is a sludge processing approach that includes the dehydration of sludge to produce a powdery, granular, sludge-derived fuel (SDF), and subsequent energy recovery from the fuel combustion. The Hyperion plant is located in Los Angeles, CA, in a nonattainment air basin, and compliance with new source review (NSR) provisions of the Clean Air Act is the most constraining requirement in terms of design. In addition to NSR rules, Los Angeles adopted a policy that air emissions from the plant should not be increased as a result of the HERS Project. Present plant air emissions are summarized in Table IV-1. These emissions result primarily from the use of digester gas in reciprocating diesel engines. As part of the HERS Project, these engines will be retired from service and replaced by a gas-turbine, combined-cycle system. Projected emissions from the latter facility under year 2000 conditions are also presented in Table IV-1. The differences between present plant emission sources that will be retired and the future gas-turbine engines emissions represent offsets available for the SDF combustion system. Based on previous combustion studies, expected air emission factors, the availability of control systems, and available emission offsets, NO_x was judged to be the most constraining of the air pollutants. NO_x, CO, and hydrocarbons will be controlled by the temperature and stoichiometric conditions maintained in the combustion process. Particulate emissions will be controlled by a multiclone in series with a fabric filter baghouse. A three-stage wet scrubbing system will be used for control of acid gases (i.e., SO_x, HCl, HF) and condensible particulates.

Table IV-1. *Plant air emission offsets for HERS system (pounds per day).*

	NO_x (as NO_2)	SO_x (as SO_2)	TSP	NMHC (as CH_4)	CO
Existing reciprocating engines using digester gas (to be retired from service)	1,800	660	225	650	1,740
Gas turbine combined cycle system (year 2000 conditions)	680	20	55	25	715
Offsets available for fluidized-bed system	1,120	640	170	625	1,025

kg/day = 2.205 × lbs/days

Essentially all fuel ash will be carried from the combustion system with the exhaust flue gas. While some dropout is expected in the boiler, particulate loading on the baghouse will remain high. The multiclone is designed to reduce ash loading on the baghouse and to remove any large particles that may not be fully combusted. The presence of such "sparklers" is considered unlikely based on the fuel particle-size distribution and gas residence time in the combustion system. Fly ash collected in the pilot combustion tests contained less than 1 percent fixed carbon, an indication of essentially complete combustion. Nevertheless, the multiclone adds an additional measure of safety to assure that hot particulates do not burn holes in the bag material. The multiclone will also remove sufficient particulates to allow flue gas recycling from ahead of the baghouse if necessary. The baghouse will be an electrostatically augmented or conventional, multicompartment, pulse jet type with a maximum net air/cloth ratio of 3.0. Baghouse technology is considered as Best Available Control Technology (BACT) by the local regulatory agency. Based on fly ash particle-size distributions measured in the pilot combustion tests and expected baghouse removal efficiencies for the particle-size fractions, an outlet loading of solid particulates less than 0.005 gm/m^3 (0.002 gr/dscf [grains/dry standard cubic feet]) should be achievable.

Soluble Gas Removal in the HERS System

Two Venturis and a tray tower in series comprise the three-stage wet scrubbing system. The system is designed to maximize use of wastewater secondary effluent and centrate from dewatering, both of which are readily available within the treatment plant. Secondary effluent is a high quality water that contains about 200 mg/l alkalinity. Centrate is less desirable from a quality standpoint but contains about 4,500 mg/l alkalinity. The Venturis are supplied with sufficient secondary effluent to neutralize expected mass emissions of acid gas. Centrate will be used as necessary to augment the alkalinity. The tray tower is used as a polishing scrubber and will use a sodium sulfite/bisulfite scrubbing liquor with pH maintained by NaOH addition. Since plant effluent will neutralize most of the acid gases, use of NaOH is not cost-prohibitive. Another advantage is that the liquid sidestream, composed primarily of soluble sodium bisulfite, can be easily disposed of with the treatment plant effluent. Use of lime or limestone for scrubbing would result in a solid precipitate that would have to be land-disposed.

The wet scrubbing system will also cool the flue gas to within 6 °C (10 °F) of the water temperature. An exit flue gas below 38 °C (100 °F) is expected from the tray tower. In the pilot combustion tests, flue gas cooling and wet scrubbing were shown to be effective in removing condensible particulates. The HERS design provides a high liquid/gas ratio and the maximum cooling possible with available water supplies. Subcooling below the saturation vapor temperature in the scrubbing system will remove substantial water from the flue gas and aid in steam plume suppression. Cooled flue gas from the tray tower is reheated about 1.7 °C (35 °F) in the induced draft (ID) fan and then mixed with 120 °C (250 °F) exhaust gas from the gas-turbine, combined-cycle system. The combined gas flow is discharged through a single stack at about 104 °C (220 °F).

Current Regulatory Requirements in Europe

Neither the separate incineration of sewage sludge nor its coincineration with household refuse comes under special regulations, but is covered by the general legislation that governs all waste incinerators. Apart from this, the legal conditions for incineration of waste vary from country to country. Whereas in some countries incineration plants are approved on a case-by-case basis, in other countries there are uniform countrywide regulations. These standards may go as far as to cover requirements for site location and design, operating methods, emission limits, control of residues, contingency plans, personnel training, financial responsibility, recordkeeping, reporting, monitoring, and inspection.

In the Federal Republic of Germany, the construction and operation of sewage sludge incineration plants is approved under a plan approval procedure.

The Federal Government has issued general administrative regulations, with particular attention to the following:

- Emission limits that are designed to prevent harmful effects and that must not be exceeded;
- Emission limits that reflect the latest state of technology and that may be exceeded; and
- The procedure for the establishment of such limits.

The following are details of the emission limits set in the Technical Instructions for Maintaining Air Purity of 1974, now under revision: a negative pressure must be maintained in the feed bunker, and bunker foul air must be fed to the furnace; minimum temperature of 800 °C (1470 °F) must be maintained, at minimum O_2 content of 6 percent by volume with a minimum residence time of 0.3 seconds. Emission levels follow:

Dust	100 mg/m^3
Chlorine compounds as Cl	100 mg/m^3
Fluorine compounds as F	5 mg/m^3
Carbon monoxide	1,000 mg/m^3

(All related to an O_2 content of 11 percent by volume)

The optical density of the waste gas plume shall be better than No. 1 on a Ringelmann chart (assumed equivalent to 20 percent opacity). In addition, the responsible plant approval authority can set lower limits for the emissions mentioned above or set limits for other emissions such as SO_2, NO_x, or heavy metals.

As far as environmental requirements for disposing of incinerator ash residues and fly ash residues are concerned, both are treated as municipal solid waste and disposed of in sanitary landfills in accordance with requirements for municipal solid waste that are designed mainly to protect groundwater and surface water from contamination by leachate. In some cases, special precautions must be taken against dust pollution while discharging the residues on the landfill site.

If liquid effluents such as those from wet scrubbing systems must be disposed of, they may need further treatment prior to discharge, depending on local circumstances. Neutralization, sedimentation, biological treatment or even evaporation may be required. Often these effluents need not be treated separately but can be pumped back into the sewage works and handled together with the wastewater.

In Dordrecht, Holland, the raw flue gases contain fly ash and harmful gases including HCl, HF, NO_x, and SO_2. Electrostatic precipitation would remove only the solid particles, not the harmful gas. Before flue gases can be passed through electrostatic precipitators, it is necessary to cool them down to 250°C (480°F). This cooling can be achieved by means of the steam production in a waste heat boiler, dilution with quench air, or evaporation of water in the gas stream. Steam production was rejected for economical reasons, the argument being that the installation was too small. Also, there was some fear that the growing proportion of halogenated plastics present in the refuse would cause excessive corrosion of the boiler tubes and result in excessive down time. It is important to realize that these evaluations date back to the 1960s, when energy conservation concerns were not prevalent.

Lowering the flue gas temperature by adding air requires that the suction (ID) fan and electrostatic precipitators be three times larger. This in turn means larger investments and electricity consumption. The temperature of the flue gases can also be lowered by evaporating water injected into the gas stream. By cooling the flue gases to such a temperature that only part of the water evaporates, polar gas molecules can be expected to dissolve in the water phase. Thus, not only the solid particles, but also harmful gas components are removed.

The temperature of the wash water as well as the flue gases must not exceed 70°C (158°F) after the washing process. Because of the choice of radial flow scrubbers, electrostatic precipitators were not required. The required water is obtained at minimal cost by using the effluent of the wastewater treatment plant. For a refuse furnace with a capacity of 7,500 kg/h (16,540 lb/hr), each scrubber is supplied about 90 m^3 water/hr (23,760 gal/hr), of which 20 m^3/hr (5,280 gal/hr) is evaporated. The scrubbed and cooled flue gases are saturated with water at 70°C; this causes a stack plume on release into the atmosphere. By tangential introduction of the scrubbed gases into the stack, water droplets are caught by centrifugal force and flow to the drain. Not only fly ash but also HF, HCl, and to a lesser extent SO_2 will go into solution in the remaining wash water. The average results of gas scrubbing are given below:

	Raw flue gas (mg/m³)	Scrubbed (mg/m³)	Reduction (percent)	Emission (kg/h)
HF	15	0.6	96	0.1
HCl	850	75	91	9.2
SO_2	280	155	45	17.6
Fly ash	4,400	110	98	13.2

After mixing with the wash water (70 °C, 158 °F), the temperature of the waste water increases about 8°- 12 °C (47° - 54 °F). This temperature increase causes a lower viscosity and therefore improved presedimentation as well as higher bacterial activity. This, in turn, creates an improved treatment capability, especially when atmospheric temperatures are low. After the scrubbing process, zinc, lead, copper, cadmium, and chrome have been found in the wash water. These metals (particles) partly settle in the washwater (scrubber drain) sedimentation basin. The wash water flowing back into the wastewater treatment plant thus contains heavy metals after sedimentation.

Due to the differences in the refuse composition, the concentrations in the waste water vary widely as shown in the following table:

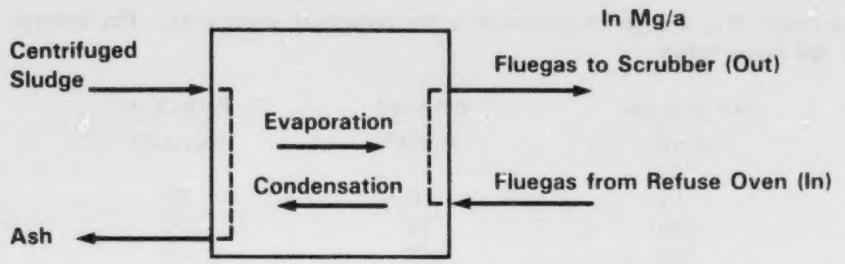
	Typical values (Mg/1)	Range (Mg/1)
Zn	10,000	5,000-18,000
Pb	1,000	500-3,000
Cu	300	120-500
Cd	150	40-250
Cr	120	30-100
Ni	50	20-80
Ag	10	3-20
Hg	1	

There were fears that these amounts of heavy metals would adversely influence the biological treatment process, but investigations have demonstrated that this concern was not justified.

Fates of Heavy Metals at Dordrecht

At the Dordrecht STP, investigations have shown that heavy metals such as Cd, Cr, Cu, Ni, Pb, and Zn are mostly recycled in the installation. The raw flue gases contain a significant amount of these metals. As indicated previously, most of these are washed out. A proportion of the metals settles in the sedimentation basin, while the remaining fluid is brought back to the incoming wastewater. In the treatment plant, the heavy metals are settled or adsorbed on the sludge, while a small proportion is released with the effluent of the installation.

In sludge incineration, the metals show different behavior because of differences in volatility. While the volatile compounds or elemental metals Cd, Pb, and Zn evaporate in the sludge furnace into the flue gases, the less volatile compounds of Cr, Cu, and Ni appear in the bottom ash. In Figure IV-1 a flow diagram is given, showing that 83 percent of the Cd, 60 percent of the Pb, and 33 percent of the Zn in the sludge are evaporated in the MHF, where the sludge is retained for a



				Fluegas	
		Cd.			
Sludge	0,31	0,26	Out	0,44
Ash	0,05	→	In	0,18
		Pb.			
Sludge	5,20	3,06	Out	4,85
Ash	2,14	→	In	1,79
		Zn.			
Sludge	16,0	5,10	Out	20,80
Ash	10,9	→	In	15,70
		Cr.			
Sludge	0,18	0,03	Out	0,17
Ash	0,21	←	In	0,20
		Cu.			
Sludge	0,93	0,04	Out	0,43
Ash	0,97	←	In	0,47
		Ni.			
Sludge	0,06	0,05	Out	0,03
Ash	0,11	←	In	0,08

Figure IV-1. Heavy metals flow in the multiple-hearth furnace at Dordrecht.

relatively long period of time. Of the heavy metals in the flue gas from the refuse incinerator, approximately 75 percent of the Ni, 20 percent of the Cr, and 10 percent of the Cu are condensed. In sum, much more of the metal compound is evaporated than is condensed (about 8 tons of metal a year). In Figure IV-2 the flows of heavy metals are given for the WWTP. The computations are not exact, since amounts per year are multiplied by a mean concentration. For example, for the ingoing and outgoing quantities, the loading to the installation (sedimentation) is five times the load in the influent wastewater. This means that a major part of the heavy metals recirculates several times before being discharged in either ash or effluent. Nearly 20 percent of the heavy metals originate from the influent wastewater, 50 percent from the flue gases of the refuse incinerator, and 30 percent from recirculation (mainly from volatilization in the MHF and from "clean" wash water and centrate). Outgoing proportions are 55 percent in the ash, 35 percent to recirculation, and 10 percent in the WWTP effluent.

Current Regulatory Requirements in Japan

Sulfur oxides, dust, nitrogen oxides, and hydrogen chloride contained in exhaust gas from sewage sludge incinerators are regulated by the Air Pollution Control Law, and odorous substances contained in the exhaust gas are regulated by the Offensive Odor Control Law.

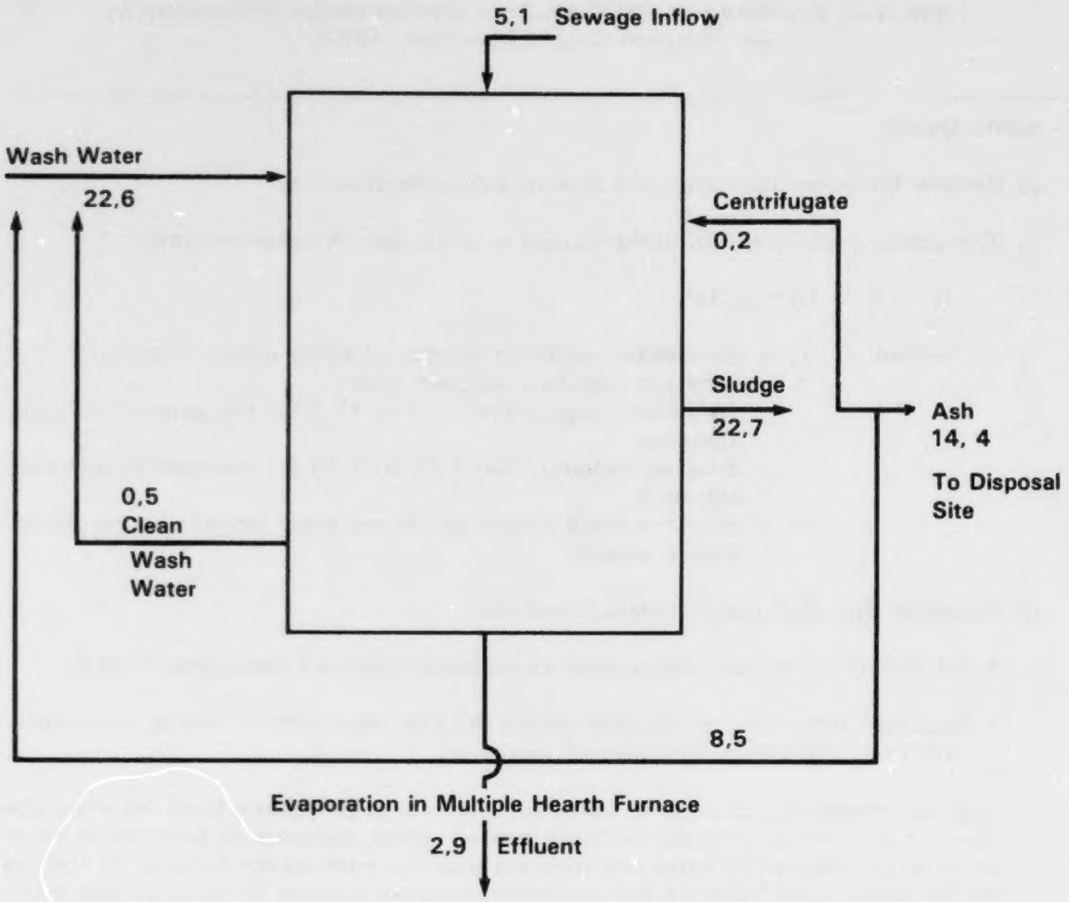

5,1 Sewage Inflow
Wash Water
22,6
Centrifugate
0,2
Sludge
22,7
Ash
14, 4
To Disposal
Site
0,5
Clean
Wash
Water
8,5
Evaporation in Multiple Hearth Furnace
2,9 Effluent

Figure IV-2. Heavy metals flow at the Dordrecht STP (in tons/yr).

Air Pollution Control Law. The Air Pollution Control Law was enacted in 1969 but was later amended several times, each time stepping up regulation stringency or increasing the number of substances and facilities covered by the regulation. Table IV-2 summarizes the regulation of exhaust gas from sewage sludge incinerators by the Air Pollution Control Law as of January 1983. The regulation of dust and nitrogen oxides, as recently revised and stepped up because the national environmental standards for ambient air quality compliance rates for suspended particulate matter and nitrogen dioxide were low, is summarized in Table IV-3. Emission standards are comprised of general emission standards, special emission standards, areawide pollutant load control standards, fuel use standards (relative to sulfur oxides), and more stringent prefectural standards.

Table IV-2. *Emission gas standards from sewage sludge incinerators by Air Pollution Control Law (Jan. 1983).*

A. **Sulfur Oxides**

a) General Emission Standards and Special Emission Standards

The emission standard for sulfur oxides is called the "K-value regulation."

$$Q = K \times 10^{-3} \times He^2$$

where Q = permissible emission volume of sulfur oxides (Nm^3/hr)
K = constant specified for each area
16 values ranging from 3.0 to 17.5 for the general emission standard
3 values ranging from 1.17 to 2.34 for the special emission standard
He = effective stack height (m, actual stack height plus height of smoke ascent)

b) Areawide Pollutant Load Control Standards

- 24 regions have been designated as areawide pollutant load control areas.
- Specified factories are factories where the fuel consumption rate is more than 100 to 1,000 l/hr on the basis of heavy oil.

c) Fuel use standards concerning sulfur content rate of petroleum fuels are stipulated for soot and smoke emitting facilities located where seasonal air pollution is caused to a high degree by small and medium sources, such as for heating, as well as for the small-scale factories and establishments not subject to the areawide pollutant load control standards in the designated areas.

d) More stringent prefectural standards cannot be issued.

B. **Dust**

a) General Emission Standards and Special Emission Standards

Type of Furnaces	Exhaust Gas Volume ($\times 10^3$ Nm^3/hr)	General Emission Standards (g/Nm^3)	Special Emission Standards (g/Nm^3)
Continuous Furnaces	more than 40	0.15	0.08
	less than 40	0.50	0.15
Others	—	0.50	0.25

Table IV-2. *Emission gas standards from sewage sludge incinerators by Air Pollution Control Law (Jan. 1983). (Continued)*

b) Measured concentration is applied for the time being. In the future, the concentration calculated by the standard oxygen concentration collection method will be applied.

c) More stringent prefectural standards can be issued.

C. **Nitrogen Oxides*†**

Type of Furnaces	Exhaust Gas Volume (x 10^3 Nm^3/hr)	Time When Incinerators Were Installed until 6/17/77	from 6/18/77 until 8/9/79	after 8/10/79
Continuous Furnaces	more than 40	300	250	250
	less than 40	300	300	250
Others	—		250	250

* Unit is cm^3/Nm^3.
† Use the standard oxygen concentration collection method.

b) Areawide Pollutant Load Control Standards

- 3 regions have been designated as areawide pollutant load control areas.
- Specified factories are factories where the fuel consumption rate is more than 1.0 to 10 kl/hr on the basis of heavy oil.

c) More stringent prefectural standards can be issued.

D. **Hydrogen Chloride**

a) General Emission Standard

- 700 mg/Nm^3.
- Use the standard oxygen concentration collection method.

E. **Remarks**

a) Target incinerators are incinerators with an incinerating capacity of 200 kg/hr or more.

b) Special Emission Standards are applied for new and expanded facilities in areas where facilities are concentrated and where serious pollution can be expected to be caused.

c) Areawide Pollutant Load Control Standards are applied for the designated regions where factories and workshops are so clustered together that it is considered difficult to meet the environmental air quality standards only by facility emission standards. Total mass emission reduction plans in the designated regions are prepared by prefectural governors and areawide pollutant load control standards are applied for specified factories larger than a specified size.

Table IV-2. *Emission gas standards from sewage sludge incinerators by Air Pollution Control Law (Jan. 1983). (Continued)*

d) Standard Oxygen Concentration Collection Method (Standard oxygen concentration for sewage sludge incinerators is 12 percent.)

$$C = \frac{9}{21 - O_s} \times C_s$$

where:
C: collected concentration of the substance
O_s: oxygen concentration in the emission gas (%)
C_s: measured concentration of the substance in the emission gas

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Offensive Odor Control Law. The major legal weapon against offensive odors is provided by the Offensive Odor Control Law of 1971. According to the law, prefectural governors are obliged to designate "Regulated Areas" where it is necessary to prevent offensive odors for the protection of amenities and to limit the emission concentration of specific odorous substances from the factories and places of business within the areas. While WWTPs and pump stations would normally be classed with the factories in the law, sewer lines were made exempt. Legal limits on odorous substances are given in Table IV-4. These substances are the principal sources of offensive odors and have been listed since methods have been established to measure their concentration in the air. The limits have been established based on those concentrations that the majority of people in regulated areas will accept. Thus, prefectural governors are obliged to set concentration limits on odorous substances within 2.5-3.5 points of the six-grade classification of odor strength (see Tables IV-5 and IV-6). The Environment Agency has so far advised prefectural governments to limit concentrations to 2.5-3.0 points in residential areas and to 3.0-3.5 points in industrial areas. Most governments have set limits at 2.5 points for residential areas and 3.0 or 3.5 points for industrial areas.

The Offensive Odor Control Law stipulated that limits are to be established in terms of (1) concentration in the air at the plant boundary; (2) concentration of gases at the stack outlet; and (3) concentration in industrial effluent. There is as yet no practical method of calculating concentration in industrial effluent. Concentration limits for gases at the stack outlet are set to maintain satisfactory ground-level concentrations at the plant boundary.

While the Offensive Odor Control Law has been effective to some extent, there still is much left to be desired. One problem concerns methods of measuring odorous substances. Usually an odor is sensed even when its concentration is very low, so the personal judgment of local inhabitants often comes into conflict with instrument measurements. Because of this, odor control by organoleptic testing is being considered instead of instrument analysis of the eight listed odorous substances. Among these methods, the triangle airbag method (a kind of air dilution method) developed by the Tokyo metropolitan government is considered quite effective, and some local governments have already specified it in pollution control regulations.

Table IV-3. *National environmental standards for ambient air quality and compliance rates.*

		Compliance Rate (%)		
	Standard	General Air Pollution Monitoring Station	Automobile Exhaust Monitoring Station	Remarks
Sulfur Dioxide	Daily average of hourly values shall not exceed 0.04 ppm, and hourly values shall not exceed 0.1 ppm.	98.4	–	
Carbon Monoxide	Daily average of hourly values shall not exceed 10 ppm, and average of hourly values in eight consecutive hours shall not exceed 20 ppm.	100	99.1	
Suspended Particulate Matter[1]	Daily average of hourly values shall not exceed 0.10 mg/m³, and hourly values shall not exceed 0.20 mg/m³.	29.2	–	
Nitrogen Dioxide[2]	Daily average of hourly values shall be within the range between 0.04 ppm and 0.06 ppm or below.	3.8 24.4 71.8	38.2 45.9 15.9	0.06 ppm 0.04 0.06 ppm <0.04 ppm
Photochemical Oxidants[3]	Hourly values shall not exceed 0.06 ppm.			

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[1] Suspended particulate matter shall mean airborne particles of 10 microns or less in diameter.

[2] a) In an area where the daily average of hourly values exceeds 0.06 ppm, efforts should be made to achieve the level of 0.06 ppm by 1985.
b) In an area where the daily average of hourly values is within the range between 0.04 ppm and 0.06 ppm, efforts should be made so that the ambient concentration be maintained around the present level within the range or not significantly exceeding the present level.

[3] Photochemical oxidants are oxidizing substances such as ozone and paroxiacetyl nitrate produced by photochemical reactions (only those capable of isolating iodine from neutral potassium iodide, excluding nitrogen dioxide).

Table IV-4. *Odorous substance limits according to Offensive Odor Control Law of 1971.*

Odorous substances	Limits: Air-borne at Plant Boundary	Concentration (ppm)
Ammonia	1 to 5	(1)*
Methyl Mercaptan	0.002-0.1	(0.002)
Hydrogen Sulfide	0.02-0.2	(0.02)
Dimethyl Sulfide	0.01-0.2	(0.01)
Trimethylamine	0.005-0.07	(0.005)
Dimethyl Disulfide	0.009-0.1	(0.009)
Acetoaldehyde	0.05-0.5	(0.05)
Styrene	0.03-20	(0.4)

* Example figures in parentheses are for Yokohama City.

Table IV-5. *Odorous substances and their odor strengths.*

Odorous Substances	Odor Strength 1	2	2.5	3	3.5	4	5
Ammonia	0.1 ppm	0.6 ppm	1 ppm	2 ppm	5 ppm	1 × 10 ppm	4 × 10 ppm
Methyl Mercaptan	0.0001	0.0007	0.002	0.004	0.01	0.03	0.2
Hydrogen Sulfide	0.0005	0.006	0.02	0.06	0.2	0.7	8
Dimethyl Sulfide	0.0001	0.002	0.01	0.05	0.2	0.8	2
Dimethyl Disulfide	0.0003	0.003	0.009	0.03	0.1	0.3	3
Trimethylamine	0.0001	0.001	0.005	0.02	0.07	0.02	3
Acetoaldehyde	0.002	0.01	0.05	0.1	0.5	1	1 × 10
Styrene	0.03	0.2	0.4	0.8	2	4	2 × 10

Table IV-6. *Six grades of odor strength.*

Odor Strength	Description
0	No odor
1	Barely detectable (detection threshold level)
2	Barely identifiable level of odor (identification threshold level)
3	Easily identifiable
4	Strong odor
5	Very strong odor

Gas Cleaning in Japan. The greater concern for removal of acidic constituents (chemical scrubbing) in Japanese regulations, as compared with U.S. regulatory practices, is exemplified by the following process description at the Yotsuya Wastewater Treatment Facility (WTF) in Takoka City, Japan. The exhaust gas is first cooled, dehumidified, dedusted, and alkali washed in a cylcone spray-type scrubber, using secondary and effluent and caustic soda. The exhaust gas is then deodorized by passing it through an acid scrubber and a sodium hypochlorite scrubber, driven by a fan and further dedusted by a wet-type electrostatic precipitator, and mixed with hot air from the shaft cooling exit to prevent white plume from the stack when discharged.

The greater concern for chemical scrubbing in Japan apparently results from the practice of keeping the furnace exit temperature as low as possible to save fuel and using chemical methods to control organics and odor constituents in lieu of afterburning.

CONTROL OF SLAGGING AND CLINKER FORMATION

A significant problem facing operators of combustion systems is prevention of ash fusion that results in formation of glassy slag or porous agglomerates called ''clinkers.'' Two case histories presented in this publication provide valuable information on the subject: the Duluth startup (see Chapter III) and the downflow gasifier research at the University of California at Davis (see Chapter V). The problem of slagging and clinker formation has particularly been found in sludge combustors burning cake produced by dewatering processes that incorporate either polymer or thermal conditioning of sludge. This finding is dramatic when such a process is put in place following an earlier period of burning a dewatered sludge produced with inorganic chemical conditioning, such as by ferric chloride and lime addition. The much lower softening and fusion points of the ash result in more rapid formation of clinkers and slag. An example of this occurred at the Metro Plant in the Minneapolis-St. Paul area and is described in the case history that follows.

Slagging Problems in the Twin Cities

Sludge cake has been burned at the Metro Plant in the Minneapolis-St. Paul area since 1938. One of the earliest multiple-hearth installations in a wastewater plant is located there. Lime slurry and either ferric chloride or ferrous sulfate were used for many years and continued to be included after the addition of four new furnaces in the 1968–72 period when an added load, secondary treatment sludge, had to be handled. The newer furnaces were fitted with open-register burners, which turned out to be a source of massive slagging difficulties. These conditions were alleviated when the burners were changed to the sealed-in type, and slag formation was essentially eliminated during the period 1976–1981.

The four newer furnaces were then shut down for modification to a configuration more suited to burning the sludge solids then being produced in the new thermal conditioning process just started up. The ash from the resulting solids was found to have a fusion point of 1,100°–1,150°C (2,000°–2,100°F), compared to the 1,400°–1,500°C (2,500°–2,700°F) values typical of the former ash, which included residuals of the ferric chloride and lime along with the natural sludge mineral content. Another type of cake was also produced in newly installed dewatering units; this was roll-pressed raw primary that had been conditioned by polymer. This also had a low fusion point typical of natural sludge mineral matter. The result of trying to burn these two new types of feeds at temperatures as high as 980°C (1,800°F) (observed by thermocouple at the furnace wall and obviously higher in the flame zone of the bed and in drop holes) was the gradual closing of the out-hearth drop holes and the development of draft difficulties in a matter of weeks. Corrective action included reducing loading and thus reduced the production rate of the furnace. Other steps were (1) reducing the maximum temperature of the hottest hearth to 870°C (1,600°F) and (2) increasing the size of the drop holes in hearth two where the plugging was most severe.

Slagging is increased by the presence in the ash of lighter metal oxides or carbonates, such as from sodium and potassium. Another constituent that has been implicated is vanadium, which is often found in fuel oil. Ferric phosphate has also been known to flux or form a eutectic, causing ash to form slag at lowered temperatures. As has been discussed in the Duluth case history, calcium and magnesium appear to raise the softening point, and thus the addition of limestone or dolomite has the dual advantage of lessening slag trouble and absorbing sulfur dioxide. Plants that continue to use lime for conditioning and stabilizing of the sludge get this added benefit.

The earlier problem experienced at the Metro Plant, and mentioned previously, was the rapid formation of slag in the tiles of the open register burners that did not have the premix features of the sealed-in type that replaced them. Analysis of flame dynamics indicated that there was a zone in the flame envelope where the gas mixture passed through zero excess air. The problem was most noticeable when oil was being burned, as was typical for much of the winter when an interruptible gas supply was off. The apparent source of the trouble was the passage of fly ash through the influence zone of the burner flame, where it was exposed to very high temperatures due to transitory conditions in the flame envelope where the fuel to air mix was zero excess air. Thus the ash particle might be heated to the theoretical maximum of over 1,800°C (3,200°F) in a fraction of a second. As it cooled when blown away, it could remain "sticky" and adhere to burner tiles or refractory brick surfaces, gathering other similar particles in a short time. This gave rise to two types of costly maintenance: buildup in the burner tile that could block the flame and cause heat to back up into the burner box and damage components, and buildup on the roof of the hearth, in the form of stalactites as in a cave. These effects caused a deflection of the flame that eroded the brick surfaces of the hearth roof and wall by the play of flame at approximately 1,500°C (2,800°F) against brick rated for 1,200°C (2,200°F) duty. Even after the change to the sealed-in burners, the deterioration problem was not completely solved. It was found necessary to set the new burners to a leaner ratio, so that the theoretical flame-tip temperature of the mix could not exceed about 1,400°C (2,500°F). This unfortunately reduced the total heat that the burners in critical hearths could inject into the furnace and thus reduced the ability to evaporate moisture and the tonnage loading the furnace could handle. The reason for this adverse effect is that the sealed-in burners are air-limited; that is, they have a maximum passageway for air and this controls the amount of airflow at a given supply pressure. The leaning-out, then, can only be done by reducing maximum fuel flow. As a result, furnaces that were thought capable of 11 to 12 tons/hour wet cake feed rate could only handle about 9 maximum, and the workers typically ran at 7 to 8 tons. However, long online times became possible — up to 11 months without trouble, instead of 3 to 4 months as before. Also, previously it had often been necessary to shut down an individual burner because of slag buildup, thus reducing the productivity of the furnace until the burner was serviced.

THE ROLE OF REGULATORY AGENCIES

Federal, state, and local regulatory agencies have a strong voice in the decisionmaking process relating to the design and construction of municipal sludge burning systems. The following discussions present viewpoints of Federal and state officials. The state aspect presents a candid review of the factors that must be considered by an applicant for a permit to avoid costly delays in getting the request through the procedural steps leading to approval.

Sludge Management Task Force Project

EPA embarked on an effort to evaluate the costs, benefits, and environmental effects of the disposal and use of sewage sludge across all media—air, land, and water—with the goal of developing a comprehensive policy and guidelines for sludge management. Consideration of the relative merits and problems facing the use of sludge combustion processes in managing municipal sewage sludge is an important aspect of this multimedia examination of sludge management practices. This effort also includes a serious attempt at undertaking a cross-media comparison of the risks associated with the different sludge management alternatives on a common basis. Stated simply, the central issue is:

> How does one manage a complex and variable waste in an environmentally protective and cost-effective manner when the disposal/utilization may involve any medium?

In response to this concern and the perceived need to provide better guidance to local managers of wastewater treatment facilities, EPA management initiated the current project in early 1982. The effort is being carried out by a staff task force under the sponsorship of a policy committee comprised of the Assistant Administrators for Water and for Solid Waste and Emergency Response and the Associate Administrator for Policy and Resource Management. The principal objective is a multimedia examination of sludge management with the development of a cohesive agency policy on sludge management as the central product. Specific outputs will include comprehensive guidelines, a series of recommendations concerning revisions to existing regulations or development of new ones, and recommendations for a continuing program in the sludge management area.

Scope and Objectives. The task force is focusing on sludge resulting from sewage treatment at publicly owned facilities and will evaluate all major disposal and use options: ocean disposal, land disposal (landfills and land applications), thermal destruction, and distribution and marketing.

Project Approach. The project is structured around a comparative assessment of environmental hazards, costs, and benefits of various disposal/utilization options using selected contaminants or sludge properties as indicators of environmental concern. Data and information for this analysis are being supplied by a number of distinct tasks, most of which are being carried out by contract consultants.

Risk Assessment Efforts. The careful comparison of risks across sludge management alternatives against the costs and benefits associated with each practice and of controls placed on these practices are key elements of the project. Medium-specific legislation and protection programs at the Federal, state, and local levels across the country have rarely addressed the intermediate side effects to determine where efforts to control one resource (e.g., air quality) should be limited so as not to overburden another resource (e.g., oceans, groundwater, or farmland). The problems that must be faced when making such comparisons are tremendous; for example, local conditions vary widely, many of the real or potential effects of sludge disposal and utilization practices are poorly understood, and technical judgments and decisions — particularly cost estimating — must rely on countless assumptions.

Thermal Conversion. Thermal conversion systems (i.e., incineration, starved-air combustion, codisposal, thermal conditioning, etc.) represent only one of the major types of sludge control technologies being addressed by the task force. These systems have frequently been plagued by their need for large capital investments and highly trained operators, serious equipment and operation problems, increasing fuel costs, and tightening emission control requirements. Fuel prices, emission requirements, sludge characteristics, operating procedures, and operator experiences different from those that were assumed by project designers have often led to serious system problems that were expensive to solve. However, under the right circumstances thermal conversion processes have been implemented as cost-effective and environmentally acceptable sludge volume reduction and disposal options. Generally subject to economies of scale due to their requirements for substantial capital investments and energy inputs (either to dewater the sludge or in the form of auxiliary fuel), these systems have not often been cost-effective for plants below 10 mgd. The recent dramatic increases in fuel costs (three- to fivefold since 1970) have resulted in abandonment of many of the existing thermal conversion systems that were designed and/or built during the days of cheaper energy because they have become too expensive to operate. Increased air emission constraints have also led to problems in operating many of the existing systems.

Recent efforts to retrofit existing thermal conversion equipment and modify inefficient operating methods (e.g., operating at lower temperatures with less excess air) have led to substantial fuel savings and improvements in equipment performance and compliance with air pollution requirements by a number of previously inefficient incineration and thermal conditioning systems. More recently installed incineration and thermal conditioning systems have also been designed, built, and operated to be much more energy efficient, corrosion resistant, and less polluting. By combining the most recent advances for effective sludge dewatering with energy efficient incineration, energy recovery/reuse equipment, and efficient emission control equipment and system operation, it should now be possible to design thermal conversion systems to be nearly self-sustaining (energywise) and environmentally acceptable. However, total system capital and operating costs and recent concerns over the potential for classification as "hazardous waste" of the ash from certain incineration systems will likely continue to confront greater use of thermal conversion systems.

Conclusion. The ongoing task force efforts should result in a better understanding of the status of each of the major sludge management options and allow for better consideration of their benefits and risks relative to each other. A serious attempt will be made to compare the virtues and problems facing thermal conversion practices with those of other major sludge management options.

PROJECT DELAYS ENCOUNTERED FOR SLUDGE COMBUSTION FACILITIES

There are a multitude of obstacles that can stall or stop the implementation of a project. Causes of delay are divided into technical deficiencies (e.g., incomplete submissions and inadequate alternative analyses) and obstacles relating to the decisionmaking environment (e.g., political impacts at the local and regulatory level, regulatory changes and coordination, problems with individuals, and public opposition).

The implementation of new, nearby, and cost-effective disposal facilities is foremost in the minds of many treatment plant operators and authorities, but permit applicants for new facilities frequently complain that the permitting process is long and expensive. Of all the sludge management modes, the implementation of new sludge combustion facilities may be the most complicated of all the disposal modes to work through the regulatory process.

The speed with which a long-term disposal mode can be implemented can have a significant impact on the operating costs for the facility. A stalled project can be devastating to a facility in both the short and long run. There are many reasons why a project may become stalled altogether. Some of the reasons are technical and others relate to the decisionmaking environment, and the blame for the stalled project may rest with the applicant, the regulatory agency, the consultant, the public, or all four. The result, however, is usually the same — project delays are expressed in higher costs that the public must ultimately bear.

Technical Reasons for Project Delays

There are two general reasons for project delays: (1) incomplete project submissions or (2) inadequate alternative analyses. In most cases, the responsibility for incomplete submissions rests with both the regulatory agency and the consultant. Either the consultant has failed to fully educate himself on the regulatory requirements or the regulatory agency has failed to fully communicate the submission requirements. The responsibility for the inadequate alternative analyses rests most frequently with the consultant or the applicant. Either the applicant has placed unrealistic restrictions on the alternative selection or the consultant has failed to objectively evaluate the variables leading to selection of the disposal alternative.

Incomplete Project Submissions

Incomplete submissions are more common for sludge combustion projects than for any other type of sludge management project. The reason that incomplete submissions are so common is that sludge combustion projects result in four separate discharges that involve air, water, and solid waste disposal regulations. The complexity of each of these programs is so great that the project review staff of one program is rarely knowledgeable in the requirements of others, so they may proceed with approvals without recognizing the permit requirements of other programs, to the detriment of the project itself. Primary attention is focused on stack gases for these projects, and the majority of proposals are considered fully completed if they have provided for emission control devices that will enable the combustion facility to meet air quality standards. However, the proposal must also address controls of the particulate emissions of the ash as it is stored, handled, and transported within the working areas of the facility; it must address the ultimate disposal of the ash; and it must address treatment and disposal of scrubber water. Although a few proposals may escape one, or perhaps two, of these requirements in the complexity of the regulatory review, it is difficult to predict which requirements may be overlooked. Generally, gambling on escaping requirements is not worth the price of the delays that occur when the deficiencies are identified and planning or calculations must be reworked.

Stack Emissions. Complete submissions for stack gas emissions will vary from project to project depending upon many parameters, including the quantity and quality of pollutants to be discharged, ambient air quality, proximity of populations, weather and topographical conditions, dimensions and shape of the stack, fuel quantity and quality, type of emission control device, and type of incineration unit. Permit requirements address the construction of the facility and its operation (source information). In fact, the complexity and variability of the submission requirements is so great that the New Jersey Air Pollution Control Program has developed a four-page instruction sheet for completion of that state's permit application, and New York has a 17-page instruction booklet.

Mistrust of Submission Information. Sometimes submissions on sludge management projects are deficient for reasons other than the complexity of the regulatory process. The deficiencies often reflect efforts to conceal impacts or multiple emission sources to avoid regulation. These types of deficiencies result in the greatest project delays because the consultant or applicant may not be willing to cooperate fully in satisfying the regulatory requirements. Under these conditions, submission information is usually forwarded piecemeal as it is requested by the agency and is accompanied by protests regarding the need for the additional information. Agency reviewers are usually well aware of the behavior of the consultant who is trying to avoid regulation. More often than not they respond with closer scrutiny of all the information on the application because the reviewer is sensitized to the possibility of concealment or deception in the project documentation.

Particulates from Ash Residual: Ash Storage and Conveyance Areas. There is a second area of air emissions that is frequently overlooked — particulate emissions from the ash residual. The transport and handling of this material can necessitate applications for additional permits or, at the very least, modifications in the operations and maintenance manual for the facility. Ash generated by a combustion facility must be removed to a final disposal site; more often than not, it is stored onsite until its volume justifies hauling to a landfill. Conveyance to the storage site and the storage site itself may expose the ash to air transport if designs do not provide for enclosure of these facilities. Where ash is pumped in a slurry to be dried and stored in lagoons, the conveyance is not an air emission concern, but particulate transport from the dried, stored ash continues to require emission controls.

Particulates from Ash Residual: Ash Within Facility-Enclosed Working Areas. Particulates from ash can become a health problem within facility structures where plant operators are exposed to this risk on a daily basis. The problem can stem from both facility design and poor operation and maintenance. Regardless of the chemical analysis of the ash particulates, the mere exposure to the respiratory irritation of particulate-laden air within the working space is a health concern issue for operators and a liability concern for employers. Designs should be carefully reviewed prior to submission to the agencies to assure that all measures have been taken to reduce operator exposure to ash particulates. If these measures include venting to the outside, air permits would be required for each vent.

Disposal of Ash. In addition to the particulate emissions from the ash, the ash itself is a discharge problem that every sludge combustion proposal must address. Although the volume of sludge ash residual is less than 10 percent of the volume of the dewatered sludge, ultimate disposal of this solid waste still requires resolution. More often than not, the solution is landfilling, and a choice must be made between hauling to a commercial landfill or construction of a facility landfill.

Disposal in a commercial landfill has become increasingly difficult to secure. Many commercial landfills have become sensitized to enforcement for environmental or health impacts. In New Jersey, for example, solid wastes are commonly subjected to a waste classification procedure that utilizes the EP Toxicity Test to determine whether the waste is compatible with the licensing limitations of the landfill. Beyond this classification check, many commercial landfills in New Jersey are now requiring additional toxicity testing for 129 priority pollutants for their own protection. Public opposition to landfilling has grown as a result of experiences with the uncontrolled dumping practices of the past; today, construction of new landfills in New Jersey is at a virtual standstill, and capacity in existing landfills is dwindling rapidly.

Hauling costs to remote landfills must also be taken into consideration. These factors usually drive consultants to the consideration of onsite disposal of the ash, either in a lined landfill or a pond. Where landfills are proposed for the project, most air permitting reviewers and consultants will recognize the need to apply for a permit; however, disposal in onsite drying ponds may not be recognized as a landfill. A project may be well under way before the need to apply for a landfill permit is noted. The project is then determined to be technically deficient for lack of the necessary landfilling submissions, and delays are incurred while information is developed for the landfill permitting agency.

Scrubber Water. The fourth combustion facility discharge that is frequently overlooked is the scrubber water. Since most sludge combustion facilities are an integral component of the WWTP, thermal process flow diagrams routinely designate scrubber water to "return to the head of the plant"; in other words, out of sight, out of mind. But this is, of course, wishful thinking; the quality and quantity of the return stream must be evaluated for its impact on the operation of the treatment plant.

Whereas air quality and stack emissions may permit the incineration of additional volumes of sludge, treatment plant performance and discharge and surface water quality standards may not permit additional volumes of scrubber water. Such was the case when expansion of the combustion facility at the treatment plant in Wayne Township, NJ, was sought. It was hoped that expansion of the Wayne incinerator would be accomplished to process sludge from other treatment plants in the state that were unable to locate disposal alternatives as a result of closure of sludge landfills; such was not to be the case because the treatment plant could not hydraulically accommodate the scrubber water.

Where treatment plant overload is a concern, direct treatment and discharge should be considered, but scrubber water is difficult to treat because incineration destroys biologically degradable organics. Successful treatment must then involve physiochemical processes, which are expensive to construct and operate.

Combustion projects may be stalled or completely blocked because of the costs of disposing of scrubber water. If this disposal problem is not identified until design and permitting of the air quality consideration is near completion, it is extremely expensive to return the project to the early planning stages and begin development of another disposal alternative. Therefore, early planning for sludge combustion should address disposal of scrubber water as an integral component of the feasibility studies and before investments have been spent in detailed planning and design.

Summary of Discharge Considerations. During development of sludge combustion proposals, consultants must be meticulous in their attention to solutions for each of the four discharges from these facilities (stack emissions, particulates from ash, ash, and scrubber water), and agency reviewers must be sensitive to the regulatory interests of their sister agencies so that deficiencies can be identified early in the project planning process. It is a tragedy when a combustion project has completed planning and design stages only to discover that disposal costs for scrubber water or ash cause this alternative to exceed the costs of other sludge management alternatives such as land application.

Regulatory submissions should be short, simple, and to the point. Maps, tables, and graphs should be used wherever possible, and the text should be confined to summaries and conclusions. The bigger document is not necessarily the better document, and the most impressive submission is the one that secures all the necessary approvals in the shortest amount of time.

Inadequate Alternative Analyses

A third technical reason for project delay is the inappropriate project. When a combustion project is initiated through the air permitting agency, it is of no concern to that agency whether the combustion disposal mode is an appropriate management alternative for the particular sludge problem. The application is ordinarily handled solely on the merits of its ability to meet air emission requirements. It is of no consequence that pelletizing or land application might be more cost-effective or environmentally sound solutions to the particular problem. Air permitting agencies are not in the business of sludge management; their business is air quality protection. Therefore, when projects are processed through the air permitting program, it is usually the public that raises the issue of the appropriateness of combustion reduction for the problem. Usually the public becomes involved when the user costs are disclosed, at which point environmental and public interest groups and neighboring communities are asked for lower cost solutions to sludge problems. Since the cost of proper sludge disposal is many times more expensive than the old dumping practice that may have been used, any cost increase may be considered too great and will trigger demands for evaluation of other alternatives.

Consultants are well advised to perform their alternative analyses with every expectation that the selected alternative will be questioned. Unfortunately, user costs are not usually disclosed until the development of the project is nearing completion, and selection of another alternative means abandonment of previous work. The unfortunate consultant who has advanced the project may find himself facing a difficult cost problem if he has not performed a thorough alternative analysis. Will expended costs plus the costs to reevaluate a less costly alternative outweigh continuing with the existing proposal in the face of public opposition? This eleventh-hour dilemma can be avoided if the evaluation is properly conducted in the initial stages of project development.

Applications for sludge combustion projects that are initiated through sludge management programs or the 201 Federal Wastewater Grant Program should focus on alternative analyses in initial planning stages. These analyses become the primary concern of both the applicant and the agency long before publication of the public notice on user costs. Although development and review of the alternative analyses may be a lengthy process, if properly performed, these functions identify cost problems before excessive effort has been spent to develop an alternative that cannot be defended against public opposition.

Presentation of Alternatives

The variables that should be included in the alternative analysis of a sludge management project are discussed in the following paragraphs. Because the future of landfilling and ocean disposal alternatives is questionable at best, the discussion focuses on the comparative concerns between land application and combustion of sludge.

Alternative analysis begins with evaluation of the sludge quality and quantity. Generally, treatment plants that receive large volumes of industrial wastes should be concerned about the suitability of their sludge for land application. Incineration looks like a viable solution for these sludges at the first cut. Unfortunately, areas with high levels of industrial wastewater discharge are usually the same ares that are limited for air emissions due to industrial and other discharges to the air. In addition, these areas are usually remote from available properties for land application. Transportation costs for land application proposals become a significant consideration for these projects.

The alternative analysis for such sludge problems resolves itself into an analysis of the costs involved in cleaning the sludge through pretreatment versus reduced application rate over an expanded land area plus the cost of hauling. These costs are then compared to the costs of pretreatment versus the costs of higher emission controls and management of the ash, ash particulates, and scrubber water for a combustion disposal mode for the same sludge problem.

Alternative evaluation for sludge projects in rural nonindustrial areas seldom results in selection of combustion modes because land costs are lower than those in urban areas, suitable land application sites are usually available at short hauling distances, and the smaller size treatment plants usually do not require the technically skilled operators needed to manage combustion facilities. This does not mean that all urban projects should automatically select combustion and all rural projects should select land application. In some situations, the time for implementation may be the determining factor. Time is, of course, money in the face of escalating costs, and planning, design, and construction of combustion projects is a lengthy process even under the best conditions. Land application may prove much more feasible for some projects to implement when time factors are taken into consideration.

The experience of the Philadelphia sludge management program is a valuable case in point. Philadelphia had the resources to secure the skilled operators necessary to manage a sludge combustion facility. Sludge quality and quantity and the proximity of suitable disposal sites all weighed against selection of a land application alternative. Their Northeast treatment plant in particular had a serious problem with high concentrations of cadmium in the sludge. This may be one of the greatest problems land application projects must face, yet Philadelphia has one of the most successful land application programs in the country today—encompassing composting, reclamation of strip-mine areas, and widescale marketing to the public and a multistate nursery industry. Why did Philadelphia choose the land application route instead of incineration? They were faced with a 1981 deadline to cease ocean disposal of sludge, so that the time required for implementation of each alternative became the critical issue. The cadmium problem was addressed through institution of stringent pretreatment requirements and strong enforcement of those requirements. The Philadelphia case is important because it points up the importance of pretreatment in the alternative analysis for sludge management.

In New Jersey, sludge analyses have indicated a mercury problem in that state's sludge. Mercury is always a cause for concern in incineration projects because emission control technology is questionable, at best. To compound the problem, the Passaic Valley Sewerage Commission (PVSC) facility is located in Newark, where ambient air quality already poses a serious problem for the implementation of any combustion proposal. PVSC is presently playing out its appeal options to continue ocean disposal. Should they lose their arguments for continued ocean disposal, the mercury issue will demand that they evaluate the alternative of high technology air emission control costs versus institution and enforcement of a pretreatment program.

These examples touch briefly on many of the variables that merit consideration in an alternative analysis for sludge management: sludge quality and quantity, hauling costs, costs for management of the four combustion facility discharges, cost and availability of suitable land, air quality, water quality, and pretreatment. Failure to accurately evaluate management alternatives will most assuredly result in the project being stalled by either the public or the regulatory agency.

Decisionmaking Reasons for Project Delays

Delays that relate to the decisionmaking environment are not as easily remedied as delays for technical reasons. First of all, they often appear to be beyond the control of the project. The proposal may be textbook perfect, but the project may still encounter interminable and frustrating delays while costs escalate. The problem may be political, one of personalities, or lack of experience. It may rest with the applicant, the consultant, the agency, or the public.

Political Environment. The political environment is the prime example of the source of delays that are beyond the control of the project managers. Although decisions on sludge disposal projects should ideally be technical and financial, they are often controlled by the political climate surrounding the project. Changes in political climate are frequently accompanied by directives to reevaluate the previous decision on the project; the longer a project takes to complete the planning, design, and implementation stages, the greater is its exposure to this type of change.

Local Elections. The most obvious political reason for project delay is a change in local control. Where proposals have become the center of controversy they are almost guaranteed to become a major issue. When they become political issues rather than technical issues, local support for the project may be completely reversed following local elections.

There is a fine line between the consultant who recognizes that he is working for the local government to implement a solution to the government's sludge disposal problem and the consultant who works for the local government to implement the project the government believes it wants. Consultants are hired because they possess the regulatory and technical knowledge that the applicants lack. Consultants and regulatory reviewers work with sludge management projects on a daily basis, but the vast majority of applicants may see only one sludge project in a lifetime. The consultant who turns project decisions over to the applicant without educating the applicant to make the decisions does himself and his applicant a disservice.

When a consultant is hired to solve a particular sludge problem, he should exercise care not to permit the proposal to become associated with a particular faction. Before beginning work on the project, he should assist in the education of all interested parties on the technical, cost, and regulatory considerations and involve them in resolution of issues.

Public and bipartisan support for a sludge management proposal does not necessarily assure project implementation. There are two other traps at the local level to which a project can fall prey. One trap is controversy over authority membership. Sludge management projects are frequently developed on a regional basis. Regional sludge planning is generally performed on behalf of area facilities by a municipality or sewerage authority acting as a lead applicant or by a loosely formed planning group comprised of representatives from facilities within the regional planning area.

At completion of the planning process, decisions about membership in the regional authority may be raised. Project implementation may be stopped dead in its tracks if the lead agency refuses to extend its voting membership on the authority to include planning participants, insisting that customer contracts be drawn. Nonmembership planning participants may then withdraw their project endorsement, fearing they will have no voting control over the costs imposed upon them for use of the facility if they are relegated to the role of customer. Without regional involvement in the project, it is impossible for the lead agency to fund the proposed project. A regional project is far too large for the needs of the lead agency alone, and, in fact, had the project been developed solely for the use of the lead agency, an entirely different project might have been selected.

Months or years of planning can go down the drain with these standoffs, and there is no easy solution to this problem. Both applicants and consultants should be aware that this problem can occur in any regional project that extends beyond member municipalities. It is, therefore, advisable in these regional situations to resolve the issue before planning begins.

Controversies over facility ownership are identical in concept to the authority membership problem. The difference is that they occur during development of codisposal projects where the solid waste management agency and the sewerage agency are separate. Each agency may assert its right to facility ownership while the project flounders and costs escalate. Consultants should approach this problem as they would the previous situation. The issue should be resolved before any time, money, or effort has been spent on the codisposal alternative. If it cannot be resolved, the sludge project should go forward independently.

Funding for Sludge Combustion Facilities

Wastewater facilities programs have been affected by significant reductions in funding for the 201 Grant Program. The timing of this funding loss has been particularly difficult for sludge projects. It was not until the recent years of the 201 Program that the magnitude of the sludge problem was identified. The bulk of New Jersey's sludge management projects did not appear on the state's priority list until 1979-80.

When faced with a major program change such as this, the applicant and the consultant may look to the agencies for assistance. For example, there are opportunities within the development of the 201 Priority List Methodology that will permit sludge management projects to realize the greatest possible advantage under the present funding circumstances. New Jersey's priority methodology, for example, has placed most of the state's sludge management projects in the innovative and alternative category where they are awarded the highest number of project priority points.

If a shift in program emphasis is identified as the reason for a project's delay, the applicant (or consultant) may be tested. Dealing with changes in program emphasis should begin long before the program changes occur. Some changes have widespread public support; the change in emphasis to hazardous control programs was illustrative of this political climate. At such times constructive remedies should be recommended to state and Federal representatives that will make the program changes less damaging to projects that are being processed, and contingency implementation plans should be developed.

Contingency implementation plans are a frequently ignored remedy that deserves some discussion here. Most applicants who are caught in the middle of a change in program emphasis feel as if the rug has been pulled out from under them. If the change in program emphasis merely means that the project will be delayed, contingency plans should identify an interim disposal option until the long-term project can be implemented. However, if the change in the program is more damaging (e.g., a change in funding eligibility or an increase in emission control requirements, both of which may raise project costs above what the applicant is able to pay), contingency plans must be more involved.

Development of contingency plans can be approached in several different ways. Facility sizing can be adjusted to make the project more economical. This adjustment can be either an increase or a decrease. An increase in size may produce increased emissions with attendant increased emission controls, but these increased costs may be economical if the combustion facility is able to draw compensating revenues from customers using the facility. A reduction in initial facility sizing may lower emission control requirements and costs for the facility. A smaller volume 5- or 10-year phased facility may then be brought online while financing for future years' volumes is developed.

Alternative funding sources should always be sought. This approach is applicable regardless of the contingency plan. The applicant should investigate private funding for development of the facility. Placing the full faith and credit of the municipality behind the private developer will lower private financing costs and create investment interest in the private sector.

Finally, a new sludge management plan may have to be developed. As previously discussed, a pretreatment program may become a necessary component of the new alternative analysis. The reduction in emissions it achieves may make the original project financially feasible again, or it may make a land application alternative feasible as it did for Philadelphia. In most cases, sludge management staff in the agencies will give assistance in the development of contingency plans if requested. However, it is clear that the change in program emphasis may be a difficult obstacle to project implementation.

Regulations

Air Permitting Program. Projects are dependent on their ability to secure funding and necessary permits. Permits are primarily regulated through the Clean Air Act, although the Water

Pollution Control Act controls discharge of scrubber water. Funding may be regulated through the state or Federal grant programs or by local contracts laws if it is a private funding source.

The two regulatory programs that have had the greatest impact on sludge combustion facilities have been the 201 Wastewater Facilities Grant Program and the Air Emissions Permitting Program, which combine to address both the funding and the permitting requirements for combustion projects. All of the new proposals for sludge combustion projects under consideration in New Jersey today, for example, were developed through the Federal 201 Grant Program. Both the 201 and the Air Emissions Programs have been touched upon in earlier discussions. The programs have two different purposes that are not necessarily coordinated or complementary.

It is the purpose of the 201 Grant Program to provide funding to construct the most environmentally sound and cost-effective solution that will correct an identified source of water pollution caused by unacceptable discharges of domestic sewage and residuals. The Air Emissions Permitting Program, however, has the purpose of assuring that air emissions will not cause violations of the air quality standards or hazardous substance emission standards.

Comparing these two purposes, it can be seen that cost evaluation and alternative evaluation are not a consideration in the air permitting program. It is also apparent that the scope of the air permitting program is much broader than combustion of sludge, and, in fact, it is estimated that sludge facilities may represent as little as 1-2 percent of the total number of projects being processed through the New Jersey Air Permits Review Section. Most air permitting activity is on more routine projects such as vents, storage tanks, and spray facilities.

In New Jersey, sludge combustion projects are grouped together with fossil-fired utility plants and major refining projects and classed as "Major Projects." These projects have been determined to have the potential for causing significant impacts to air quality and warrant a higher degree of scrutiny than other air emission proposals. Higher scrutiny results in slower processing when compared to the vast majority of air emission permits, so applicants must not expect to secure permits within the same period of time that they obtained a permit for the pressure release valve on the gasoline storage tank at their municipal garage. Such will not be the case, and the longer review period should not be considered a delay.

Changes in Ambient Standards. Very few changes have occurred in the Air Permitting Regulations. The Clean Air Act established the National Ambient Air Quality Standards for various pollutants. In addition to these standards, EPA set separate emission standards for substances it considered to be extremely hazardous to public health and welfare. These substances include arsenic, asbestos, benzene, beryllium, mercury, and vinyl chloride and are regulated under the National Emission Standards for Hazardous Pollutants. No ambient standards have been set for these substances, and their controls are related to state-of-the-art and best available control technologies.

Clearly, these substances do not comprise the sum total of potential emissions that would be a public health concern; there are numerous other candidate substances for inclusion in the emission standards awaiting promulgation at the Federal level. Under the states' authority to promulgate regulations that are stricter than the Federal regulations, many states have moved forward with development of their own hazardous and toxic control programs, including organic and metal emission standards. New York has added 215 new substances, and New Jersey has added 11 organics.

Consultants and applicants must keep abreast of potential amendments to state and Federal emission standards that could impact their projects, and they should be prepared to submit additional technical information quickly if amendments occur midproject.

Changes in Modeling Guidance. There are two other areas of the air permitting program that applicants/consultants should watch for changes in the requirements—modeling and measurement. In 1978 EPA issued guidelines for computer modeling programs that were acceptable for use in the permitting program. Proposed revisions to those guidelines were made in 1981 and opened for public comment, but they have never been formally revised and reissued. Instead, EPA has issued an internal document, "Workshops on Air Quality Modeling," which addresses some changes in modeling techniques that relate to state-of-the-art refinements.

The consultant must keep informed of changes in the modeling guidelines because deviation from these guidelines is only acceptable where it can be justified to the satisfaction of the agency. Usually, modeling changes only require amplification of previously submitted project information, but even amplification can result in delays that would be unnecessary if the consultant remained informed of the impending program changes through close communication with the agencies.

Changes in Measurement Techniques. Measurement techniques that are accepted by the air permitting program also undergo changes based on improved instrumentation and research. Applicants and consultants should make sure their emission measurements are performed in accordance with currently accepted techniques. For example, ambient particulate measurement may be revised to measure only those particulates that are less than 10 microns in diameter.

Stack testing of total particulates can change. Obviously, if such a change in particulate measurement were to be effected during the life of the project, delays could be incurred while alternative measurement methods are implemented. Again, the best protection against this type of regulatory obstacle is advance knowledge of changes through close communication with the agencies.

Coordination of Air Permitting with 201 Grants

The 201 Wastewater Grant Program has undergone many changes since its creation in 1972. Regulations have been changed, and the Federal Water Pollution Control Act itself has undergone revision. Although previously discussed changes in program emphasis have seriously affected sludge projects in the Grant Program by reductions in nationwide funding allocations, most of the regulatory and statutory changes have not. The primary causes for project delays in the 201 Program appeared to be a result of the former three-step structure of the grant program, which is poorly adapted to the air permitting program.

Step 1 of the 201 Program was the planning phase. A planning grant was issued to an applicant upon approval of a plan of study for Step 1 and other necessary assurances. The second step of the 201 Program was design, but design grants could not be issued until completion of Step 1 (approval of the selected alternative) and issuance of a permit to construct the selected plan.

Obviously, the 201 Program does not wish to allocate grant monies for designs of facilities that can never be permitted. The air permitting program cannot issue a permit without a design, so that applicant is then in a "Catch 22" situation: he should not design without a permit and he cannot secure a permit without a design. Since enactment of the 1981 amendments to the Clean Water Act, the problem has worsened. The owner must fund the design work "up front" and hope to be reimbursed in a later construction grant.

There are several ways to resolve this problem. One approach is a program for issuance of conceptual air permits. If it is acceptable to both agencies, the project can then proceed to design. New Jersey, for example, has resolved this problem in a different way. The New Jersey Air Pollution Control Program does not give conceptual approvals of design and operation, but it has developed a process whereby approval can be given without final design completion by using key design and operating parameters of the selected combustion process and the selected air pollution control system.

The New Jersey Air Program has also developed an outline plan of study for sludge incineration projects that has been incorporated into the 201 Plan of Study for the Step 1 phase of the project. This air plan of study enables the applicant to develop necessary data for air permitting during the project planning. The air program then requires the applicant/consultant to submit a list of emission substances in pounds per hour and tons per year before and after control; at the same time, the applicant must submit results of air quality modeling if applicable (facilities emitting in excess of 50 tons/yr).

The process was not developed until some projects had been trapped by the permit design requirements, but it is to the credit of these two agencies that they were able to develop a mutually agreeable procedure that would not unduly burden future applicants. Cooperation among review agencies is the key to resolution of this problem; the applicant is helpless to resolve this issue alone.

Problems with Project Individuals

There are other delays that originate with individuals who are directly involved in managing and reviewing the project. These problems are difficult to address because they tread close to personal criticisms that are not discussed in public; but every project has the potential to encounter these types of delays.

Inexperienced Project Management. Projects can be delayed if project managers are too inexperienced to manage them efficiently; both consultants and review agencies can be guilty of this. The importance of adequate training and supervision cannot be over stressed. If there is a change in management in the middle of a project, the new project manager may unknowingly require that previously resolved issues be addressed. Such requests are usually followed by an outcry from the agency or the applicant depending on the source of the request, and a month or two may pass before the project resumes its forward motion. But management can also be inexperienced because the individual is uninitiated. In this case regulatory requirements may be overlooked and meaningful deficiencies may not be identified until the project reaches a point at which substantial revision of the planning documents and designs becomes necessary.

The inexperienced manager or reviewer may also find it difficult to make decisions. It may be the first project he has reviewed and he is afraid to make a mistake, so that every form of direction is checked with the supervisor; or it may be the first project he has ever developed and he is afraid to select an alternative that might not be the right one. Again, close guidance and training may be the only solution to this problem. Left alone, both experienced or inexperienced managers or reviewers may unduly delay making a decision. Experienced consulting and review staff can be a major asset by cooperating in informed decisionmaking.

The Ostrich Applicant. It is not uncommon for consultants and agencies to find that they are dealing with an applicant who simply does not want to be involved in the project. After the applicant has hired the consultant, he may want nothing to do with the project. The applicant may refer letters and calls from the agency to the consultant. The applicant may be too busy to review the alternative analysis, visit the proposed site, or attend briefing meetings, or participate in problem resolution. The consultant and the agencies have no power to implement the project, so it is the applicant who must ultimately finance the proposal. When it is time for the checks to be written, the project may be in a precarious position if the applicant has kept himself in the dark during development of the proposal.

Keeping the ostrich applicant educated and informed may be one of the hardest problems any consultant may face. One recommended method is for the consultant to hold a project startup meeting with the applicant in which he can present examples of sludge projects that have been implemented with their costs. Examples should be representative of similar-sized communities.

If the applicant cancels the meeting, it should be rescheduled. If the applicant suggests that the consultant proceed without him, the consultant should respectfully decline. No project should begin unless the consultant has prepared his applicant for the range of costs that could be anticipated. The meeting discussions should be recapitulated in a letter to the applicant. Similarly, when hard issues must be addressed during the course of project development, the consultant should insist on getting the applicant's opinion on important issues. Invariably, if the applicant is allowed to avoid involvement, he will question the consultant on the very same issues when the project is nearing completion, and it is costly to rework the proposal.

If the consultant continues to have difficulty getting his applicant's full attention, it is sometimes helpful to request that the regulatory agency schedule the meetings. Most agency staff are very willing to meet with applicants to discuss the project. In short, it is the responsibility of both the consultant and the agencies to keep the applicant informed and involved in the development of his project because it is *his* project, and it is he who must pay for it.

Personality Conflicts. Also included with obstacles that originate with individuals are those uncommon delays that are rooted in personality conflicts. On unpleasant and rare occasions, a total breakdown will occur between or among individuals representing applicant/consultant and the regulatory agency; or one or more of these individuals may be a cause of public animosity. It is imperative that all individuals involved in the project treat each other with respect as professionals. This begins with the recognition that each has a very important function to fulfill that may not necessarily conform to the goals and functions of the other individuals but is necessary to the success of the sludge project.

Public Obstacles

The public can also be a source of project delays. Project managers are often up against a public that opposes tax increases and refuses to allow any type of facility to be constructed in its "backyard." This opposition may require additional alternative analyses or environmental impacts, and the project is delayed for months in an effort to satisfy the public's concerns.

Although project managers (agency and consulting) are the experts in solving sludge problems, and the public is the learner, the public "pays the tab"; therefore its concerns should never be summarily dismissed. The public should be educated to understand that sludge disposal costs cannot be expected to remain at the levels of the "good old days" when dumping was uncontrolled and hauling costs were cheap.

Summary

After reviewing the long list of potential obstacles to project implementation, the technical obstacles may seem small by comparison. This is an extremely important realization for every applicant/consultant because the less exposure a project has to these nontechnical obstacles, the greater are its chances for implementation. A well-prepared technical submission will speed the project's earliest implementation.

CHAPTER V. EMERGING TECHNOLOGY

In this chapter, processes for the thermal conversion of municipal sludge are considered in four groups:

1. Gasification,
2. Liquefaction,
3. Wet oxidation, and
4. Combustion.

Each group is divided into two subgroups: (1) sludge used as the only feed material and (2) sludge processed with other carbonaceous wastes.

The processes for the thermal conversion of municipal sludge that have been supported by the USEPA's Municipal Environmental Research Laboratory (MERL) in Cincinnati, OH, are shown below.

Type of Process	Sludge Alone	Sludge Plus Other Wastes
Combustion	ICFAR*: low-air, low-burn zone in MHF (Indianapolis, IN; Nashville, TN; Hartford, CT)	Coincineration in FBF (Duluth, MN) Coincineration in MHF (Eagan, MN)
Wet Oxidation	Vertical Tube Reactor (Longmont, CO)	
Gasification		Simplex-S - lab scale UC/Davis - pilot scale Purox - prototype Andco-Torrax - prototype Wright-Malta - lab scale
Liquefaction	Battelle-Northwest Worcester Polytechnic Institute	

* Indianapolis Center for Advanced Research

GASIFICATION

The use of coal and wood to produce energy (heat or power) via pyrolysis-gasification processes has been practiced since the 18th century. The more widely used early gasification processes were the "blue-water gas" and the "producer gas" processes. These processes produced low to medium energy gas, which was used as fuel for gas engines, steam boilers, ceramic kilns, and metallurgical furnaces. In Sweden, during World War II, gas generators were used to provide fuel for vehicles, tractors, and boats. With the availability of cheaper fossil fuels (natural gas and petroleum) after the end of World War II, commercial use of coal and biomass gasification processes ceased. This was because communities were well supplied with natural gas or could "crack" propane (or other hydrocarbon gases) into a suitable utility gas at a lower cost than for gasification processes. Intensive research into pyrolysis-gasification processes in recent years has provided insights into the process fundamentals and resulted in development of new biomass gasification processes. The new generation of gasification technology is directed mainly toward production of medium to high energy gas or production of synthesis gas. To date, only small-scale, low energy gas biomass gasifiers have been commercialized worldwide. Some of the new generation technologies such as Purox and Andco-Torrax have been built in Europe, Japan, and the United States, but none has had successful operations. The major biomass gasification technologies are listed in Table V-1. A detailed discussion of each is beyond the scope of this document.

With the exception of the cogasification work, only two processes have been tested on sludge: Standard Solid Fuel and DUVANT. The results of those tests have not been published, however, so this section is presented solely on the basis of theoretical considerations and by extrapolation from work with biomass.

Application to Sludge

One means of gaining insights into the applicability of gasification technologies to sludge is to consider the differences between municipal sludge and the biomass feed material.

Moisture Content. The moisture content of the biomass feed ranges from dry to as high as 70 percent with a median around 20-25 percent moisture. Approximately 75 percent of the gasifiers are operated or tested on feed materials with moisture concentrations between 10 and 40 percent. The moisture content of dewatered municipal sludge usually ranges between 60 and 85 percent. However, with some types of conditioning and dewatering, moisture levels as low as 50 percent may be achieved. To achieve moisture levels below 50 percent, some type of drying needs to be employed. Conventional dryers could easily reduce the moisture to required levels. However, there would be considerable energy and monetary costs. For instance, it would require approximately 9-16 MJ/kg (4,000-6,800 Btu/lb) of dry solids to lower the moisture content of sludge from 75 to 20 percent. Another approach to reducing moisture levels would be a dryer that is integrated into the technology. For instance,the DUVANT process produces low energy gas that is used to generate electric power using an engine-driven generator. The heat in the engine exhaust is used to dry the feed material. This approach may prove advantageous to sludge gasification. However, given the energy conversion efficiencies of gasifiers and engines and the energy content of sludges, there would be a limit to the amount of moisture that could be removed.

A third alternative is to develop gasifiers that could operate with high moisture level feed material. This is not an unreasonable course to pursue. The key considerations would be the impact of the latent heat of vaporization on operating temperature, the extent to which the moisture could be used as the agent in the steam gasification, agglomeration problems in the gasifier, and the impact of higher moisture levels on the product's gas quality. Institute of Gas Technology (IGT) researchers are working on the gasification of peat with moisture levels as high as 50 percent without predrying. The Standard Solid Fuels technology has been operated on a 70 percent moisture feed material. Thus, indications are that such an approach is not unreasonable. The last alternative is to dilute the sludge moisture levels with drier material (i.e., cogasification). The PUROX researchers have suggested that a municipal solid waste and sludge mixture with sludge moisture as high as 75 percent

Table V-1. *Gasification technologies capable of producing fuel gas.*

Technology	Type of gas	Type of gasifier	Heat source	Other factors
BSP-LURGI			Starved-air combustion	
Davy Power Gas Corp.	LEG[a]	Fixed bed	Char combustion	In commercial use
DUVANT	LEG	Fixed bed	Char combustion	In commercial use
American Fyr Feeder	LEG	Moving bed	Char combustion	In commercial use
ANDCO-TORRAX	LEG	Fixed bed	Char combustion	In commercial use
THERMEX	LEG	Fluidized bed	Char combustion	In commercial use
Molten Salt	LEG	Molten bed	External	Uses catalyst (Na_2CO_3)
PUROX	MEG[b]	Fixed bed	Char combustion	Cogasification of sewage sludge with municipal solid waste and/or other materials
SIMPLEX	MEG	Fixed bed	Char combustion	
UCD - Cogasification	MEG	Fixed bed	Char combustion	
Renugas	MEG	Fluidized bed	Char combustion	
Multi-Solid Fluid Bed	MEG	Fluidized Bed	Hot sand bed	
GERE	MEG	Moving bed	Separate char combustion	
Standard Solid Fuel	MEG	Moving bed	Separate char combustion	Uses catalyst (Ni-Fe)
Wright-Malta	MEG	Moving bed	External	
Solar Fired	MEG	Fluidized bed	Solar radiation	
Flash Hydropyrolysis	MEG	Entrained bed	Preheated hydrogen	

[a] LEG = Low energy gas.
[b] MEG = Medium energy gas.

could be successfully gasified, but they noted that dried sludge would provide optimum operation and the least capital investment because of the reduced water vapor volumes.

Feed Material Size. Gasifiers are operated on uniform feed material; otherwise, a high velocity burning channel would form in the reactor and reduce its efficiency. Shredders are often employed to produce a uniform size. In addition, several technologies require feed material in a certain size range. Municipal sewage sludge is not uniform. Grinders can be employed to produce a small, uniform, particle-sized material. However, in fixed-bed gasifiers, where bed void fraction is essential to operation, such small-sized material may cause problems. Sludge may be pelletized or briquetted; however, that requires external drying to low moisture levels or mixing with a dry material. The key considerations here are mass and heat transfer resistance and bed movement in the gasifier. Fluid-bed gasifiers and moving-bed gasifiers may prove to be most adaptable to sludge. Information is required on the characteristics of these types of gasifiers operated with sludge. Successful test runs have been made using sawdust and manure; thus it appears that any problems due to size can be surmounted.

Sludge contains contaminants such as heavy metals, but it appears that these may not be a problem. The cogasification work suggests that they are retained to a large extent in the ash. Certainly problems of gasification ash disposal and heavy metals concentrations in exhaust gases are similar to those for sludge incineration. While sludge ash content is high, it does not overwhelm the other constituents. Certainly any sludge gasification technology will have to accommodate a higher ash production rate, but it does not appear to be an insurmountable barrier.

The applicability of gasification technologies can be summarized by grouping existing technologies as follows:

1. Moving-bed gasifiers - These gasifiers can handle moisture levels up to 70 percent. They represent the best chance for high moisture sludges.

2. Fluidized-bed gasifiers - These gasifiers will be able to overcome the small-sized limitations. In addition, these gasifiers have operated with moistures up to 50 percent. With extensive dewatering and/or employing exhaust gas heat for drying, they may prove successful for sludge gasification.

3. Fixed-bed gasifiers - These gasifiers have rather strict feed material requirements. Their applicability will most probably be limited to cogasification of briquets or pellets.

Development Potential

The similarity between municipal sludge and biomass leaves little doubt that it can be gasified. The big question is how much processing it must undergo. Its highest heating value (HHV) is slightly, but not significantly, less than wood. It does not have any other constituents that will prevent gasification. In general, sludge must be dewatered to approximately 30 percent solids before it will combust autogenously. How much must it be dewatered in order for it to be gasified, and what will be the impact of dewatering on process economics and the process energy balance? Some gasification technologies have specific feed material size, shape, and density requirements. Again, these requirements do not represent unsurmountable barriers. Sludge can be ground, pelletized, briquetted, or otherwise treated to satisfy feed material requirements. The question again is one of impact upon economics and energy balance. Cogasification technology is an example of a solution to these problems. It mixes wet sludge with drier municipal solid waste and, in some technologies, pelletizes it to meet feed material moisture,size, shape, and density requirements.

Another factor bearing on the development potential of sludge gasification is its place in the wastewater treatment plant and a use for its product. Approximately 90 percent of all wastewater treatment plants are less than 44 l/s(1 mgd) in capacity (i.e., they generate less than 1 Mg (2,200 lb) of dry solids per day). Many are not located near industrial areas that can use synthesis gas. In many small plants, sludge wasting is done on an intermittent basis. All these conditions represent constraints to specific processes but not necessarily to gasification in general. It is apparent that smaller units that can be operated intermittently may find the most application. In addition, units that can be coupled with a generator to produce electric power will find greater application, since the need for fuel gas and/or steam is limited in most wastewater treatment plants and the big energy users are powered by electricity. The use of gasification technologies that produce medium energy gas (MEG) may be limited to larger plants, especially plants where 90 percent oxygen would be available and where the unit costs of cleaning, storing, and selling the gas may be more favorable.

Simplex-S Process. The Simplex process developed at Columbia University converts cellulosic waste to clean, medium Btu fuel gas through cogasification with coal. The principal innovation of Simplex is the briquetting step, where coal and cellulosic waste such as municipal solid waste or forest pulp are pressed into briquets. When these briquets are gasified in a moving-bed gasifier, the waste fibers act as wicks, absorbing the tars that cause swelling and agglomeration of caking coal. Because the briquets retain their size and shape throughout the gasifier, the flow of briquets through the gasifier zones is smooth and stable.

Simplex was originally developed for gasification of eastern bituminous caking coal and refuse-derived fuel (RDF). Municipalities, however, generate both MSW and sewage sludge, and it is natural to dispose of MSW and sludge together. Codisposal has been applied to several waste-disposal technologies such as incineration, pyrolysis, and composting. Codisposal through the Simplex method, which is called Simplex-S, has several advantages over these conventional codisposal processes. The destruction of heavy organic wastes in MSW and the safe disposal of heavy metals contained in sludge are accomplished at a relatively low cost. The nongasifiable components of Simplex-S briquets end up embedded in a glassy, nonleachable frit. Thus, they can be disposed of safely or put to use as road-building aggregates.

GASIFICATION OF DENSIFIED SLUDGE AND WASTEPAPER IN A DOWNDRAFT PACKED-BED GASIFIER

The codisposal of densified sludge and wastepaper in a cocurrent flow packed-bed gasifier represents a new application of the thermal gasification process. Advantages of this technology include lower costs than other incineration or pyrolysis technologies, simple construction and operation, and the ability to use a variety of fuels including agricultural wastes and other biomass materials in addition to densified sludge and wastepaper.

Gasification involves the partial combustion of a carbonaceous fuel to generate a combustible gas (producer gas) containing carbon monoxide, hydrogen, and some hydrocarbon gases and a char rich in carbon. A process flow diagram for a complete sludge and wastepaper gasification system is shown in Figure V-1. The key elements of the system are fuel processing, gasification, and gas utilization.

To gasify sludge and wastepaper in a downdraft gasifier, fuel processing is required. A suitable gasifier can be made from source-separated wastepaper, sludge, and woodchips by shredding, mixing, and densifying the fuel components. A densification system operated by the Papakube Corporation of San Diego, CA, was utilized to produce sludge/wastepaper fuels. The Papakube densification system includes an integral shredder, a metering system that allows moistening of the fuel to the op-

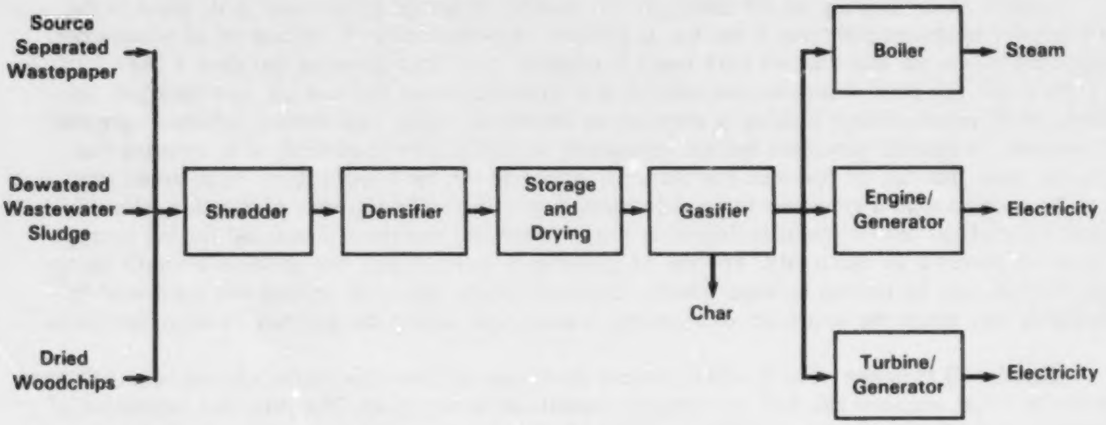


Figure V-1. Flow diagram for a complete sludge/wastepaper gasification system.

timum moisture content, and a modified agricultural feed cuber. The producer gas can be used to power an internal combustion engine to generate power or it can be used as fuel for a boiler.

Downdraft Gasifier

Developed originally to reduce the quantities of tar in the producer gas, a downdraft gasifier typically is composed of three subassemblies: (1) a fuel hopper, (2) a firebox, and (3) a char pit. Fuel flow in downdraft gasifiers is by gravity with air and fuel moving cocurrent through the reactor. The University of California at Davis, Department of Civil Engineering pilot-scale, batch-fed downdraft gasifier is shown in Figure V-2. The fuel hopper is constructed as a double-wall cylinder. The double wall acts as a condenser to remove the water vapor from the fuel prior to gasification. The inner cylinder is in the form of a truncated cone to reduce the tendency for fuel bridging. The firebox is also a double-wall cylinder. The inner cylinder is the actual firebox. Air is supplied by four tubes to the annular space between the walls that serves as an air plenum to distribute air evenly to the six tuyeres (air nozzles) that supply air for partial combustion of the fuel. The choke plate is essentially a large orifice that serves as a constriction in the gasifier firebox and is used to concentrate both the fuel and gas, creating the very high temperatures necessary to thermally crack tars. A rotating eccentric grate is located in the char pit immediately below the choke plate. The grate supports the fuel bed and allows passage of char and gas into the char pit. Producer gas is drawn off continuously through a pipe manifold on the side of the gasifier. A continuous screw auger is used to convey char from the char pit to a large char storage container. The design of the grate is specific to the fuel and operating characteristics of the gasifier.

Operating P rameters

Three important operating parameters directly affect the gasification process: (1) fuel ash content, (2) air input/gasification rate, and (3) internal gasifier temperatures.

Fuel Ash Content. In addition to lowering the energy content of the fuel, fuel ash, upon reaching its melting point in the gasifier and then cooling, forms slag. Excessive slag formation in a downdraft gasifier can block the flow of fuel and char through the gasifier and thus halt the gasification process. The tendency for slag formation is a function of the reaction zone temperature, the

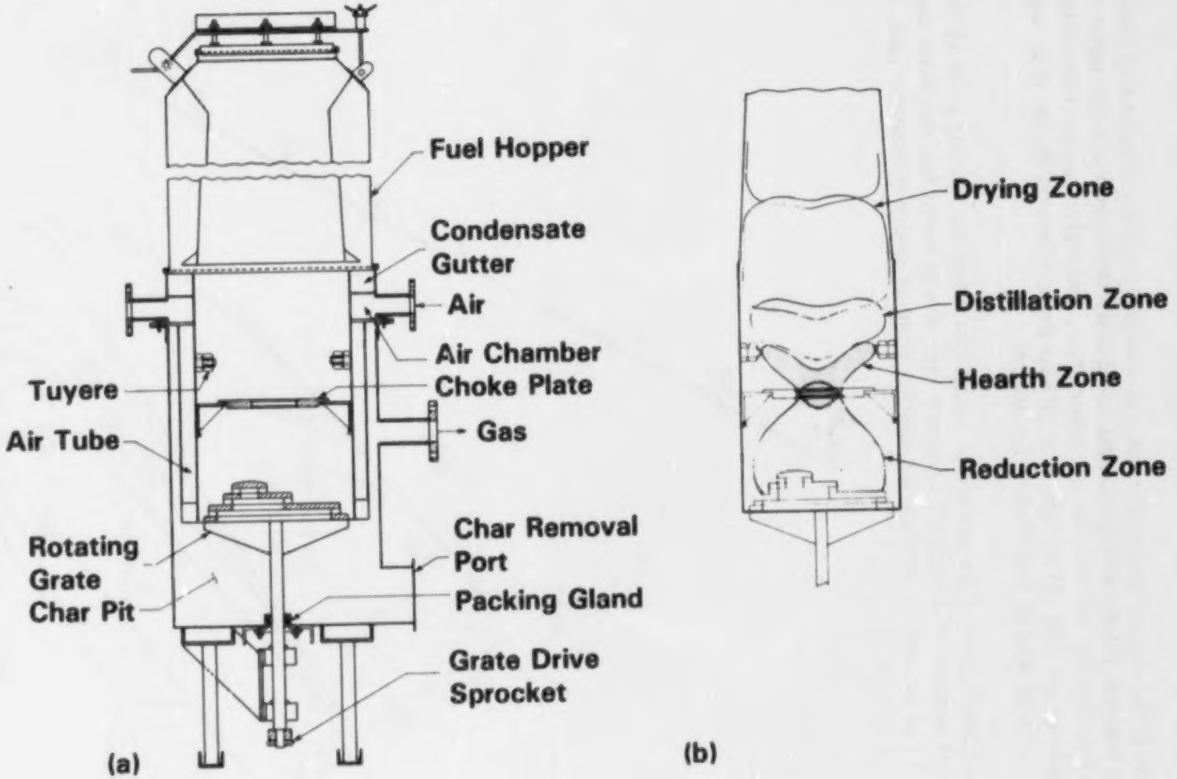

Fuel Hopper
Condensate Gutter
Air
Air Chamber
Choke Plate
Gas
Char Removal Port
Packing Gland
Grate Drive Sprocket
Tuyere
Air Tube
Rotating Grate
Char Pit
(a)
Drying Zone
Distillation Zone
Hearth Zone
Reduction Zone
(b)

Figure V-2. Schematic of UCD civil engineering gasifier: (a) internal construction details and (b) reaction zones.

composition of fuel ash, and the percentage of fuel ash. To minimize sludge disposal costs, it would be ideal to gasify only sludge in the downdraft gasifier. But because there is sufficient ash in the sludge (between 25 and 40 percent) to cause disruptive slag formations in downdraft gasifiers, slag formation in the gasification of sludge can be inhibited by lowering the reactor temperature and/or mixing additives with the sludge to lower the melting point.

Large reductions in the reactor temperature in a downdraft gasifier to inhibit slag formation are not feasible for two reasons: (1) the energy content and quality (with respect to tar vapor content) of the producer gas varies directly with the reactor temperature, and higher reactor temperatures produce a better and cleaner gas; and (2) hot spots are always present around the air inlet nozzles of downdraft gasifiers, causing slag to form below the tuyeres.

A change in the composition of the ash in the sludge can affect the melting point of the ash. Based on an elemental analysis of a sludge/wastepaper fuel, it was found that the phase diagram shown in Figure V-3 can be used to estimate the melting point of sludge/wastepaper fuel. The solid

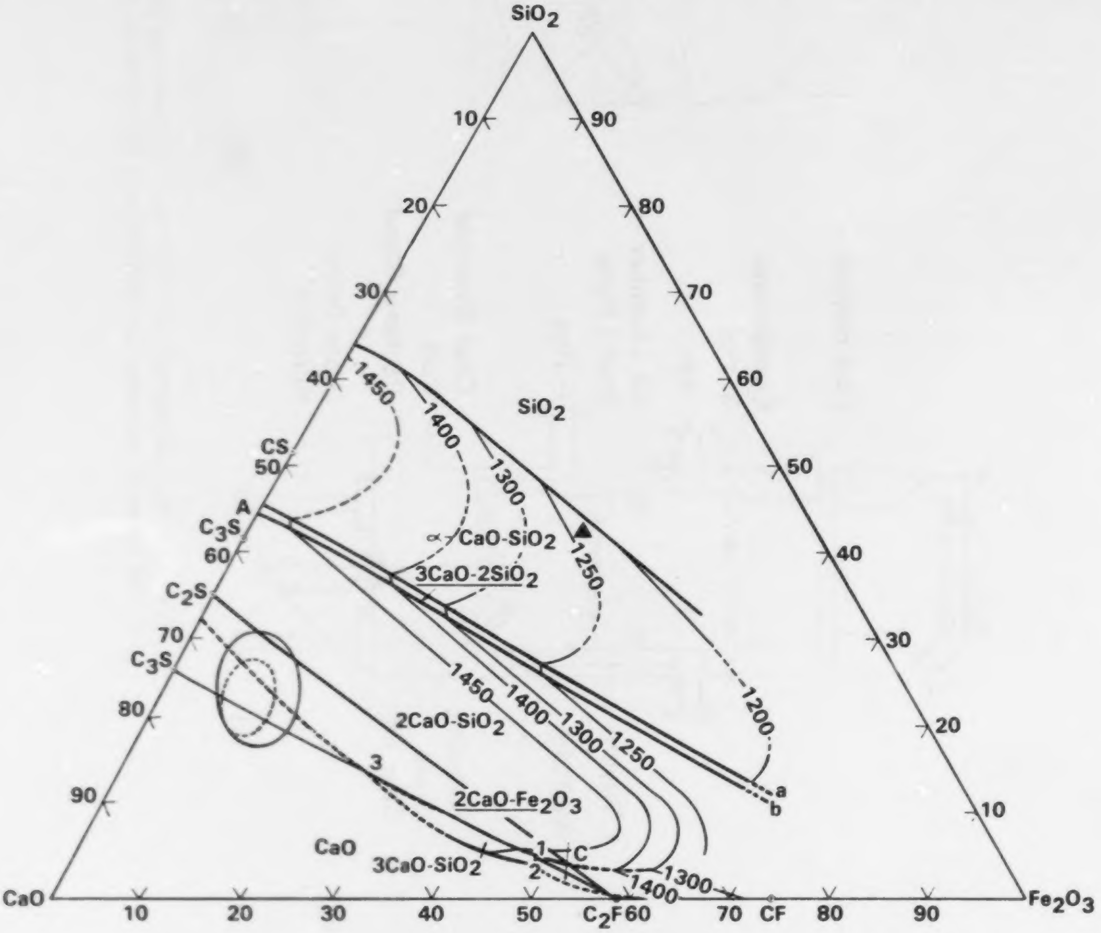

SiO_2
10
90
20
80
30
70
40
60
CS
50
A
C_3S
60
C_2S
70
C_3S
80
90
SiO_2
1450
1400
1300
1250
1200
α-CaO-SiO_2
$3CaO$-$2SiO_2$
40
30
20
10
a
b
1450
1400
1300
1250
$2CaO$-SiO_2
3
$2CaO$-Fe_2O_3
CaO
1
C
2
$3CaO$-SiO_2
1300
1400
CaO
10
20
30
40
50
C_2F 60
70
CF
80
90
Fe_2O_3

Figure V-3. Phase diagram for a CaO-Fe_2O_3-SiO_2 system.

triangle in the diagram is an estimate of the sludge/wastepaper ash melting point, about 1,250 °C (2,252 °F). If lime (CaO) is added to the mixture, it can be seen that the fuel ash melting point will be raised. (The addition of lime would move the solid triangle towards the CaO angle, located at the lower left-hand corner.)

One investigator has proposed the idea of controlling the slagging potential of sludge by adding source-separated wastepaper (a low ash fuel) to dewatered wastewater sludge. However, in municipal sludge/wastepaper gasification systems, if all the wastepaper generated in a community were to be collected and mixed with all the wastewater sludge generated, the resultant fuel ash content would be about 8.2 percent dry basis (which has been shown to cause severe slagging in downdraft gasifiers). Therefore, to derive usable gasifier fuel from a mixture of wastewater sludge and source-separated wastepaper in a community gasification system, wood chips can be added to the mixture. Because the ash content of woodchips is low (0.1-3.0 percent dry basis), a sludge/wastepaper/wood chip fuel mixture can be gasified without disruptive slag formations.

Air Input and Gasification Rate. The air input rate is the most easily controlled operating parameter in the gasification process. In the absence of changes in the fuel composition and gasifier dimensions, the air input rate directly affects the gasification rate and the temperature in the gasifier zone and indirectly affects the producer gas composition.

The specific gasification rate, defined as the gas output rate expressed in mass or volume terms divided by a characteristic gasifier area, is an operational parameter used to compare gasifiers of different sizes. It is advantageous to operate the gasifier at a high specific gasification rate. The most obvious advantage is that the cost of the gasifier is minimized. Also, a gasifier operated at a high specific gasification rate will maintain a high reactor temperature, which is necessary to maintain a producer gas of good quality.

Internal Gasifier Temperatures. The temperature reached in the reaction zone of the gasifier greatly influences all aspects of the gasifier performance. High internal gasifier temperatures affect the process in several ways: (1) tars, higher hydrocarbons, and other products of fuel distillation are thermally cracked to noncondensable hydrocarbons in the hearth zone of the gasifier (see Figure V-2(b)); (2) the chemical equilibrium for the formation of CO and H_2 is favored by high temperatures; and (3) the tendency for the formation of slag is affected greatly by the internal gasifier temperature.

Development Status

To investigate the gasification of densified sludge and wastepaper, a pilot-scale gasification system was designed and constructed. The operating system consists of three component parts: (1) the batch-fed downdraft gasifier, (2) the data acquisition hardware, and (3) the producer gas burner.

To demonstrate the gasification process and evaluate air pollution emissions, a broad range of fuels has been tested with the gasifier. Fuels tested include agricultural residue, densified wastepaper, and densified wastepaper and sludge mixtures containing up to 25 percent sludge by weight. The sludge fuels were made from mixtures of lagoon-dried primary and secondary sludge and from recycled newsprint (in full-scale systems, a mixed paper fraction of solid waste could be used). Mixtures were densified using commercially available equipment.

Preparation of Densified Fuel. It has been possible to develop a densified fuel from source-separated wastepaper and treatment plant sludge using the Papakube densification system. Bulk densities of the sludge/wastepaper fuels range from 284-595 kg/m^3 (17.7 to 37.1 lb/ft^3). The highest fuel bulk densities are associated with the largest fraction of sludge, which may indicate that the sludge acts as a binder for the wastepaper during the densification process. The physical integrity of the sludge/wastepaper fuel cubes is dependent on the moisture and sludge contents of the mixture. It was found that sludge/wastepaper cubes of the highest physical integrity are made when the moisture content of the mixture is about 20 percent (wet basis). The physical integrity of the sludge/wastepaper cubes also depends directly on the sludge content of the sludge/wastepaper mixture (over the range of mixtures tested).

Maximum Fuel Ash Content. To date, a fuel with an ash content of 4.85 percent is the highest tested without significant slag formation. Severe slagging occurred in the gasifier with a fuel having an ash content of 8.5 percent. Although the addition of lime to the fuel may eliminate some slagging in the high ash fuels, a more conservative fuel ash content of 5 percent (dry basis) can be used as a design number until more experience with full-scale sludge/wastepaper gasification systems is obtained.

Specific Gasification Rate. The highest specific gasification rate obtained with sludge/wastepaper fuels was 9,500 m^3 of producer gas (0°C, 1 atm) per hour per square meter of choke plate opening area (9,500 $m^3/hr/m^2$). This rate is close to the maximum value of 10,000 $m^3/hr/m^2$ reported by other investigators for small downdraft gasifiers fueled with wood.

Gasification Process Efficiencies. Temperature, pressure, and process rate data were taken during each experimental gasifier run. These data and the results of gas, fuel, and char analyses were used to compute energy balances and process efficiencies. It was found that the lower heating value of the producer gas generated from the gasification of sludge/wastepaper fuel varied between 5.12 and 5.76 MJ/m^3. Comparable values for sludge digester gas and natural gas are about 22 and 36 MJ/m^3, respectively.

Air Pollution Emissions. Air pollution emission tests were conducted on combusted producer gas over a series of four gasifier runs. Particle emissions were determined using modified EPA Reference Method 5; SO_2 emission concentration was determined with a modified EPA Reference Method 6. Concentrations of NO_x and noncondensable hydrocarbons were measured using gas analyzers. The results of these tests can be summarized as follows: (1) Federal particle emissions standards for incinerators were met without the use of flue gas cleanup equipment; (2) concentrations of NO_x varied between 60 and 115 ppm; (3) noncondensable hydrocarbon concentrations, based on hexane, were usually below 1 ppm; and (4) concentrations of SO_2 ranged from 0.037 to 0.098 g per dry cubic meter.

Full-Scale Gasifier Systems

There are no full-scale gasifier systems currently operating with sludge/wastepaper fuels. To acquire a full-scale gasifier system that can be used in a small community, commercially available gasifier systems originally designed to operate on wood fuels may be purchased and modified, or a gasification system specially designed for sludge/wastepaper gasification may be designed and manufactured.

Gasifier Systems for Small Communities

Important criteria for a small community gasification system are low capital costs and simplicity of operation and maintenance. A gasifier system that is designed to operate only a fraction of the day can be utilized to sell peak or partial peak power to the local power company. Highly automated gasifier systems are not needed in small communities because of the availability of relatively cheap, unskilled labor.

If a gasifier/engine/generator system is used to generate electricity from sludge/wastepaper fuels, it is recommended that: (1) the gasifier/ engine/generator system be located at the local wastewater treatment plant, (2) a downdraft gasifier be used because of its ability to generate a producer gas low in tar vapor, and (3) the gasification system be operated in a batch mode rather than in a continuous mode.

LIQUEFACTION

Liquefaction is the thermochemical treatment of hydrocarbonaceous materials to produce a synthetic oil. During the past decade, rapidly escalating costs and uncertainty of foreign petroleum resources have stimulated the development of liquefaction technology. Actually, the production of synthetic fuels from organic matter and other solid fuels is not new. Germany used a liquefaction technology during World War II. Nevertheless, most of the fundamental information on potentially competitive technologies in today's economy was developed in the past decade through quite extensive research activities, both in the private sector and under the auspices of the U.S. Department of Energy (DOE). Table V-2 summarizes the major liquefaction technologies available today.

Only one laboratory study has been done on the liquefaction of sewage sludge; thus, much of this analysis is based on comparisons with biomass liquefaction. While there is a fairly large amount of information on coal liquefaction, the differences between coal and sludge are much greater than the differences among sludge and the other biomasses, especially concerning the most important areas affecting product quality. Direct and indirect liquefaction are significantly different processes with respect to assessing applicability and development potential.

Application to Sludge

Direct Liquefaction. Three classes of direct biomass liquefaction technologies have been studied: pyrolysis, solvent-catalyst using oil, and solvent-catalyst using water. The pyrolysis technologies require a dry, finely ground feed. The solvent-catalyst technology, which uses oil as the solvent, also requires a dry, finely ground feed. Sludge would have to be extensively dewatered and ground to meet the feed material requirements of these technologies. The solvent-catalyst technologies that use water as the solvent would probably require the sludge to be ground but not dewatered beyond 20-30 percent solids.

With respect to product oil quality, it has been found that oxygen content and viscosity can be dramatically lowered by operating at higher temperatures. Studies on the two technologies have been conducted with operating temperatures between 280° and 360°C (550° and 680°F) producing oil with oxygen contents between 7 and 11 percent. By increasing reactor temperature from 330°C (630°F) to 425°C (800°F), product oil oxygen concentration was reduced from an average of 8.2 to 1.7 percent. Thus, product oil quality may be improved by higher reaction temperatures.

There is little doubt that sludge could be used to produce low to medium quality fuel oils using a direct liquefaction technology. However, there are many questions yet to be answered concerning economics and energy balance.

Indirect Liquefaction. There are two coal technologies and one biomass technology described herein as indirect liquefaction technologies. The common element is the use of steam gasification to produce either synthesis gas or a gas rich in olefins. The biomass liquefaction technology requires a dry, finely ground feed material. There are a number of gasification technologies that employ steam

Table V-2. *Summary of major liquefaction technologies.*

PROCESS CONDITIONS													
		Primary Liquefaction Reactor(s)						Secondary Reactor(s)				Material Requirements*	
Process Identification	Category	Status Maximum Capacity Hg/day	Temperature, °C	Pressure, kPa	Res. Time, Min.	Recycle** w/w	Catalyst & Chemicals	Process	Temperature, °C	Pressure, kPa	Catalyst & Chemicals	Hydrogen Consumption kg/100 kg Coal	Other Materials
COED	Pyrolysis	33	320-870	55	NA	–	–	Hydro-Treatment	400	17,000	NiMo	1.16	Oxygen Steam
Coalcon	Pyrolysis	Not Active	560	3,200-14,000	5-25	–	–	–	–	–	–	2 to 4*	Oxygen Steam
Flash Hydro-Pyrolysis	Pyrolysis	22	840	3,400	20-200 (millisec)	–	–	–	–	–	–	–	Oxygen Steam
SRC II	Solvent-Extraction	45	450-470	14,000	45-75	1.5-2.5	–	–	–	–	–	4.7	Oxygen Steam
EDS	Solvent-Extraction	230	400-430	10,000-14,000	NA	1.1-2.0	–	Solvent Hydro-Treatment	–	–	CoHo	–	–
FRI	Solvent-Extraction	Lab. Scale	400	0	6	NA	HF, H_2SO_3 $S_b \times 5$	Solvent Hydro-Treatment	150	0	NI	NA	–
ADL	Solvent-Extraction	Lab. Scale	400	690	60	NA	–	Coking	450	200	–	NA	–
H-Coal	Catalytic Hydrogenation	540	450	21,000	NA	2.4	Co/Ho	–	–	–	–	3.4	–
Synthoil	Catalytic Hydrogenation	Not Active	450	21,000	15	1.5-1.9	Co/Ho	–	–	–	–	–	–
Molten Zinc-Chloride	Catalytic Hydrogenation	1.1	380-430	14,000	15	1.5	$ZnCl_2$	Finishing & $ZnCl_2$ Combustor	500 930-980	14,000 400	Air + HCl	6.0*	Hydrochloric Acid; Zinc Chloride (0.4 kg/100 kg coal)
CO-Steam	Catalytic Hydrogenation	Bench Scale	430	28,000	120	NA	Na_2CO_3	–	–	–	–	–	Carbon Monoxide & Steam
Fischer-Tropsch	Indirect Liquefaction	Commercial	230-330	2,300-2,500	NA	–	Fe/Co	–	–	–	–	–	Oxygen Steam
MTG	Indirect Liquefaction	Commercial 13,000 kg/day	NA	NA	NA	–	Zeolite	Methanol Synthosis (ICI)	200-300	5,200-10,400	C_4	–	Oxygen Steam

NA — Not Available

*All values reported on dry weight basis of feedstock coal except asterisk, which denotes moisture and ash-free basis (maf) of coal.

**Recycle ratio (w/w) referenced to feed coal

Table V-2. *Summary of major liquefaction technologies. (Continued)*

			PROCESS PERFORMANCE								
				Liquid Product Oils							
				Oil Characteristics*							
Process Identi-fication	Category	Status Maximum Capacity, Hg/day	Yield, m³/Hg	°API**	%N	%S	%O	H/C	Heating Value MJ/k8(HHV)	Other Products	Comments
COED	Pyrolysis	33	0.19	−4 (25)	1.1	2.8	8.5	1.07	34.9	Char 60% w/w Dry coal	Final product from hydrotreatment. The liquid yields are highly dependent on coal characteristics.
Coalcon	Pyrolysis	Not Active	0.26-0.28	–	–	–	–	–	–	SNG, LPG	
Flash Hydro-Pyrolysis	Pyrolysis	22	0.28-0.38	–	0.5	0.2	–	–	–	–	Data based on 30-40% carbon conversion. Performance is highly dependent on mixing characteristics.
SRC II	Solvent-Extraction	45	0.46	5/39	0.9/0.4	0.3/0.2	3.3/3.9	1.09/1.64	40.1-45.2	SNG, LPG	
EDS	Solvent Extraction	230	0.44-0.46	−0.5/31.1	0.66/ 0.21	0.41/ 0.47	1.83/ 2.82	1.03/ 1.53	39.7-42.5	Fuel Gas	A separate reactor is required for regenerating the solvent donor in a self-sufficient plant. Product yield and characteristics are a function of recycled solvent characteristics.
FRI	Solvent-Extraction	Lab. Scale	0.70	–	–	–	–	–	–	SNG	Requires complex chemicals recovery system and involves handling of strong acids such as HF or HCl.
ADL	Solvent-Extraction	Lab. Scale	0.42-0.49	–	–	–	–	–	–	–	Data based on 44-52% coal conversion using a cyclic, batch-type process.
H-Coal	Catalytic Hydrogen-ation	540	0.52	13/32.3	0.65/ 0.42	0.29/ 9.3	–	–	–	–	High pressure reaction
Synthoil	Catalytic Hydrogen-ation	Not Active	–	–	–	–	–	–	–	–	
Molten Zinc-Chloride	Catalytic Hydrogen-ation	1.1	0.77	–	<0.025	<0.05	–	–	–	SNG, LPG	Three-stage reactor sequence with intercoolers. Involves handling of strong, corrosive materials and requires controlled conditions to keep $ZnCl_2$ in molten state.
CO-Steam	Catalytic Hydrogen-ation	Bench Scale	0.65	–	–	–	–	–	–	–	Data based on reported yield of 60% on maf coal. High pressure reaction.
Fischer-Tropsch	Indirect Lique-faction	Commer-cial	NA	–	–	–	–	–	–	LPG, Alcohols, Waxes, Phenols	Relatively complex, requiring several separating and purification stages. 80% of product is high quality gasoline.
MTG	Indirect Lique-faction	Commercial 13,000 kg/ day	0.30	–	–	–	–	–	–	LPG	

* Characteristics reported for bulk oil product except when delineated by two values representing the heavy and light distillate fractions, respectively, as follows: heavy value/light value.

** Parenthesis denotes specific gravity after hydrotreatment: without parenthesis denotes raw product.

gasification and that, with proper adjustments, could produce synthesis gas. The feed moisture requirements of these technologies range from 10 to 45 percent moisture. The steam requirements range from 0.3 to 1.0 kg/kg dry feed. Thus, for a technology like SFGM, as much as 1.4 kg of water is used per kg dry feed. This theoretically represents a feed moisture of 60 percent. Again, there is little doubt that sludge could be used to produce a fuel oil via indirect liquefaction. It would have to be dewatered somewhere beyond 40 percent solids and ground.

Development Potential

The development potential of sewage sludge as a fuel oil depends on the quality of the fuel oil, whether or not its production energy balance is positive, economics, and the type of market that develops for the oil. Work is currently being conducted to determine maximum yield, quantities, and economics of a continuous direct liquefaction process.

Energy Balance. The primary concern is that the production of the fuel oil should not be a net energy user. The primary factor affecting the energy balance for sludge liquefaction is the moisture content of the sludge. There are two direct liquefaction technologies that show promise for avoiding large energy expenditures for dewatering and drying: synthetic asphalt and indirect biomass liquefaction (IBL). However, for the IBL technologies and the other direct biomass liquefaction technologies that require a dry feed, a means of drying the sludge needs to be developed that does not have to pay the energy cost of the latent heat of vaporization of water. For instance, it requires 10-19 MJ/kg (4,400-8,000 Btu/lb) to dry sludge from 75 to 10 percent moisture using a conventional drying technology, which is basically the heating value of the sludge. Thus, a negative energy balance is essentially assured. It appears that the development potential of liquefaction technologies may be limited from an energy balance standpoint to the two direct liquefaction technologies that do not require any dewatering. One of these appears to have a positive energy balance.

Economics. The economics of direct biomass liquefaction indicate that this may be the first economical process where a return on investment for sludge disposal is realized. If a credit equal to other disposal methods is given the process, it is estimated that producing oil can pay off the capital expenditure in less than the usual commercial 3-year payback period.

Summary. It appears that the synthetic oil technology has development potential. In addition, it may prove to be the first process to have a positive return on investment for sludge disposal. The idea of a return on investment or of the value of sludge as a new resource is new and may be difficult to accept; however, even if the economics do prove positive, this process may be limited to plants that now have a large enough sludge capacity, 100 tons a day or more, to find incineration economical. However, as the process is developed a much smaller plant may be acceptable because of improvements in the process.

CONVERTING SLUDGE SOLIDS TO FUEL OIL — THE BATTELLE-NORTHWEST PROCESS

The conversion of primary dewatered sewage sludge to fuel oil and an asphalt substitute is described in the following sections. This conversion utilizes a basic catalyst at 250° - 350°C (480° - 660°F) under pressure. Energy yields of up to 70 percent of theoretical were obtained as an oil with a heating value up to 90 percent that of diesel fuel; some samples were fractionally vacuum distilled and the bottoms used in synthetic asphalt mixes. Preliminary process economics for a 100-ton/day plant suggest payback in less than 6 years using conservative assumptions. This work was based on batch processing, but continuous processing of sludge is now being studied, together with a more detailed assessment of fuel product value and the economics of operation.

Process Description

The sludge liquefaction process developed by Battelle-Northwest (B-N) is depicted in simplified form in Figure V-4. This chemical process involves alkaline digestion at high temperature and pressure and is one of a family of similar processes that has been used to liquefy "biomass."

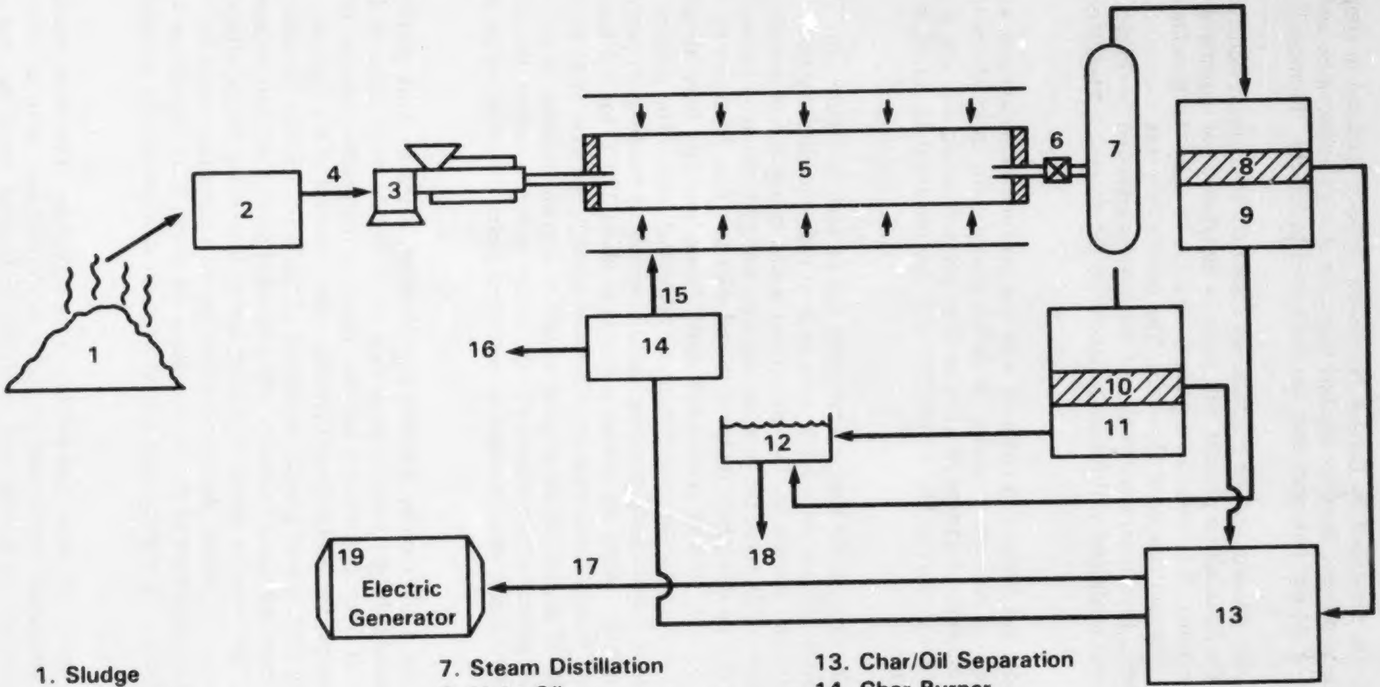
For the past 10 years, B-N has investigated the fundamental chemistry of biomass liquefaction. This led to the knowledge that the liquefaction process will work in the absence of expensive gas additions, catalysts, and organic solvents. B-N obtained a grant from EPA to study the liquefaction of sewage sludge, cofunded by the city and county of Honolulu. The liquefaction was successfully performed in batch mode (autoclaves). Preliminary economics of the process appeared favorable. B-N is now progressing to a continuous mode and will further characterize the product from sludge as a fuel.

The basic liquefaction process has features in common with wet pressure oxidation and with pyrolysis—the application of heat and pressure to sludge. It differs considerably in its chemistry. As a result, it does not yield large amounts of carbon dioxide, as does pressure oxidation, and it does not produce coke-like char, as does pyrolysis. The oil product will also remain stable at room temperature for more than 2 years.

The essential simplicity of the process for sludge conversion can be seen in Figure V-4. The sludge should be dewatered to about 30 percent solid or less, as is already practiced by many municipalities in the United States and elsewhere. The conversion works at any solids concentration up to about 90 percent, but at low solids value the process becomes energy consuming because of the amount of water to be heated. The dewatered sludge is mixed with less than 5 percent by weight of alkali (sodium carbonate, or possibly lime or cement kiln dust). Some lime may have already been added as a dewatering aid, minimizing the requirement for additional alkali. The mixture is passed into the reactor by means of a specialized pumping system capable of handling 30 percent solids in a water slurry. In the reactor, where the sludge is heated to about 320°C for 1-2 hours, it is converted to oil, char, gas, and watersoluble organics. Characteristically, the total yield of oil and char (ash-free) is between 60 and 70 percent of the original weight of organic material in the feedstock, with between 0 and 10 percent of the organics in the sludge going to carbon dioxide and water-soluble organics. On a carbon basis, this translates to combined yields of carbon in the oil and char that approach theoretical.

The B-N conceptual design for a 100-ton/day synthetic asphalt plant, based on work performed for EPA and using primary Honolulu sludge, considered using a steam-distillation of light oil as a way of separating light, volatile oil from the products and also reducing the reactor pressure prior to product recovery. Using this concept, the depressurized product, after removal of the light oil, would be transferred to a holding tank, where gravity separation of the heavy oil/char fraction would occur, leaving two layers of oil/char and water. Actually, the product separates out into wastewater and into an oil/char fraction that still contains about 15 percent water. Depending on the efficiency of separation under actual operating conditions, the supplemental use of a centrifuge could be necessary to ensure more complete separation of the oil and water fractions. Prior experience with the wastewater is that it can be treated by conventional processes in an environmentally acceptable manner.

The proportions of light oil, heavy oil, char, and ash may vary according to reaction conditions. In particular, the ash portion of the sludge carries through partly in the char and partly as dissolved inorganics in the wastewater. Heavy oil, as defined here, is soluble in acetone, while the char is not. In laboratory experiments, the equivalent fractions are defined as (1) light oil - vacuum distillable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Electric
Generator

1. Sludge
2. Dewatering
3. Slurry Pump
4. Alkali Addition
5. Reactor
6. Pressure Letdown
7. Steam Distillation
8. Light Oil
9. Waste Water + Organics
10. Heavy Oil + Char + Ash
11. Wastewater + Organics
12. Anaerobic Digestor
13. Char/Oil Separation
14. Char Burner
15. Heat to Reactor
16. Ash to Disposal
17. Oil for Process Fuel
18. Treated Water Disposal
19. Electric Power From Oil

Figure V-4. Simplified process diagram for sludge liquefaction.

below 300°C and (2) heavy oil - not so distillable, with both (1) and (2) being subfractions of the acetone extract of the total oil products. The "char" is the acetone-insoluble fraction of the total product organics. It should also be borne in mind that laboratory experiments were performed in batch conditions in autoclaves, while the conceptual design is for a continuous process—the only one that is likely to be economical. Extrapolating from batch to continuous conditions is always uncertain, so the actual proportions of light oil, heavy oil, and char obtainable in a continuous plant may vary from laboratory-scale batch results.

Other products from the liquefaction process include an off-gas (which is over 98 percent carbon dioxide with only traces of methane, carbon monoxide, hydrogen sulfide, and other undesirables) and the ash (which is distributed between the char and wastewater fractions). The char itself is considerably different from pyrolysis char. It is a fine particulate material suspended in the heavy oil and can be removed by solvent extraction. Alternatively, it can be burned with the oil.

For the work for EPA on synthetic asphalt production, payback options were calculated for each of these alternatives. Addition of a solvent extraction and solvent recovery step to separate out the char approximately doubles the payback period, but this is necessary to make synthetic asphalt. On the other hand, for fuel production, without separation of the char, the economics appear much better. It appears that this process could be the first sludge disposal process to yield a return on the capital investment.

B-N performed a series of batch autoclave reactions using sludge and either sodium carbonate or lime, under various temperature and pressure conditions. The product was compared with the sludge used as a starting material and was used to determine heats of combustion and to make a series of synthetic asphalt samples for testing at the University of Idaho; three of the samples tested out as satisfactory or superior in some respects to the petroleum asphalt test sample.

CONVERTING SLUDGE TO OIL BY HYDROLIQUEFACTION

This study was undertaken to assess the feasibility of converting municipal wastewater sludge to liquid and gaseous fuels through reactions with hydrogen at high pressure and temperature. The work was based on earlier experiments carried out in the Resource Recovery Laboratory at the Worcester Polytechnic Institute.

These studies involved the hydroliquefaction and hydrogasification over nickel catalysts of cellulosic substances slurried in paraffin oil at temperatures of 350° - 450°C (660° - 840°F) under hydrogen pressure in the range of 3-8 MPa. Under such conditions, up to 90 percent of cellulosic substances can be converted to gaseous and liquid fuels. The background, techniques, and experimental equipment associated with the cellulose and lignite liquefaction studies have been applied in the present investigation to the hydroliquefaction and gasification of sewage sludge.

Experimental Procedures

For this study, raw and digested sludges were collected from the Deer Island Sewage Treatment Plant in Massachusetts. These samples were used in experiments either as aqueous suspensions as received or as suspensions of dry sludge solids slurried in anthracene or paraffin oil.

Experiments were carried out in an autoclave under hydrogen pressure. The principal apparatus consisted of a magnetically stirred batch autoclave. The maximum safe pressure that could be applied to this autoclave was 14 MPa. Auxiliary equipment included a hydrogen-feed system, a slurry-feed device, pressure and temperature recorder-controllers, a wet-test meter for measuring the off-gas, and analytical equipment for determining the mass and composition of the liquid and gaseous products. Conditions for the oil and water slurry experiments are listed below.

Experiment	Initial H_2 pressure (MPa)	Operating temperature (°C)
Oil slurry	8.3	425 (800°F)
Water slurry	3.5	300 (570°F)

With the total pressure limited to 14 MPa, it was necessary to use lower initial hydrogen pressures and temperatures for the water slurry experiments because of the vapor pressure generated by the water. The conversion nearly reached its maximum after about 20 minutes at reaction temperature; little further conversion was observed after 30 minutes.

Results are evaluated in terms of the total fractional conversion of the toluene-insoluble organic feed into oils (pentane-soluble substances) and into other substances. These are calculated by the following relationships:

Conversion to Pentane-Soluble Oil,

$$X_O = \frac{\text{(weight of oils in product slurry)} - \text{(weight of oils in sewage sludge and carrier oil)}}{\text{(weight of organic toluene-insolubles in sewage sludge)}} \times 100$$

Conversion of Toluene-Insolubles,

$$X_{TI} = \frac{\text{(weight of organic toluene insolubles in sewage sludge)} - \text{(weight of organic toluene-insolubles in product slurry)}}{\text{(weight of organic toluene-insolubles in sewage sludge}} \times 100$$

Thus X_O represents the net oil yield per unit of insoluble organic material in sewage sludge, and X_{TI} represents the conversion of the insoluble organic material in sewage sludge to all liquid and gaseous products.

Results and Conclusions

1. Raw sewage sludge and sludge settled in digesters can be largely converted to liquid and gaseous products by heating the water slurry to about 300°C (570°F) under its vapor pressure. Conversion of up to 90 percent of the toluene-insoluble organic feed can be achieved with or without added hydrogen. Neither sodium carbonate, sodium molybdate, nor nickel carbonate catalyst significantly alters the result.

2. Significant amounts of pentane-soluble oils were not produced from the water-slurried sludge under any of the conditions studied.

3. If raw or settled digester sludge or the final effluent sludge from the digesters is dried, ground, and slurried in a carrier oil, up to 90 percent of the toluene-insoluble organic content can be converted in 20 minutes in the presence of hydrogen at a total initial pressure of 8.3×10^6 Pa and a temperature of about 425°C (800°F).

4. Under these conditions, up to 50 percent of the material so converted may be recovered as pentane-soluble oils or asphaltenes.

5. Great complexity and high projected investment and operating costs of a commercial plant are indicated by the results obtained here for dried sludge slurried with oil. These results do not encourage further development work on hydroliquefaction of sewage sludge.

Note: Conclusion 5 indicates that if the sludge is dried, then the problem of sludge disposal is solved, and conversion to oil is an unnecessary expense that will not further reduce the disposal cost of the sludge.

WET OXIDATION - THE VERTICAL TUBE REACTOR

The Vertical Tube Reactor (VTR) is a wet oxidation process developed by the Vertical Tube Reactor Corporation for the treatment and disposal of municipal sludges and industrial organic wastes. Although the thermodynamic principles involved in wet oxidation were well established by Zimpro, the VTR system is a recent and unique engineering application. It uses an extended U-tube reactor to achieve high reaction pressures and temperatures and long retention times for wet chemical oxidation. An extended U-tube configuration is achieved by suspending two concentric tubes from the top of a conventionally cased well (Figure V-5). The waste fluid and air are injected into the inner tube. As the waste stream and air flow down the well, they undergo natural pressurization due to increasing hydrostatic head. Thus, water pumps and air compressors must only be sized to overcome friction and other minor pipe losses. The high pressure experienced in the reaction zone is generated by the waste columns within the tube.

The location of the VTR reactor in a closed well in the earth results in the surrounding earth providing some of the thermal insulation for the process. During startup of the system, heat is pumped into the reactor through the reactor heat exchanger system. As the reactor is operated, the surrounding earth or rock is heated. Heat losses to the earth or rock decrease with time, until there is a near steady-state flow of heat to the rock. The design of the reactor is such that the heat of oxidation is greater than the amount of heat being lost to the rock plus the heat being washed out in the reactor effluent. When the heat produced exceeds these losses, the reactor is self-sustaining with respect to heat, and the heat exchanger system is operated in a manner that removes excess heat from the system to maintain the desired reactor operating temperatures and allows heat recovery to be used in other parts of the processing system. The high temperature expected in fullscale VTR systems will produce a lower recycle load than other wet oxidation systems that run at lower operating temperatures and hence have higher COD loads in their effluent. The VTR effluent is completely biodegradable before discharge when the system is in stable operation.

History of Process Development

In the early 1970s, the VTR Corporation began research on the problem of municipal waste disposal. Investigation suggested that an extended U-tube set in a well was a workable method for wet oxidation of municipal sludges. It was then determined, theoretically, that the thermodynamics were compatible with the reactions involved. The equilibrium configuration and hydrodynamics of bubbles in the VTR system are of great importance in establishing minimum sludge flow rates, overall system pressure drop, and maximum allowable air injection rates. The company constructed a bubble flow experiment using a clear acrylic tube to resolve the bubble flow mechanics.

VTR Corporation has developed several computer models of the process; these aid in determining optimal configurations and conditions such as reactor diameter, COD loadings, flow rates, heat

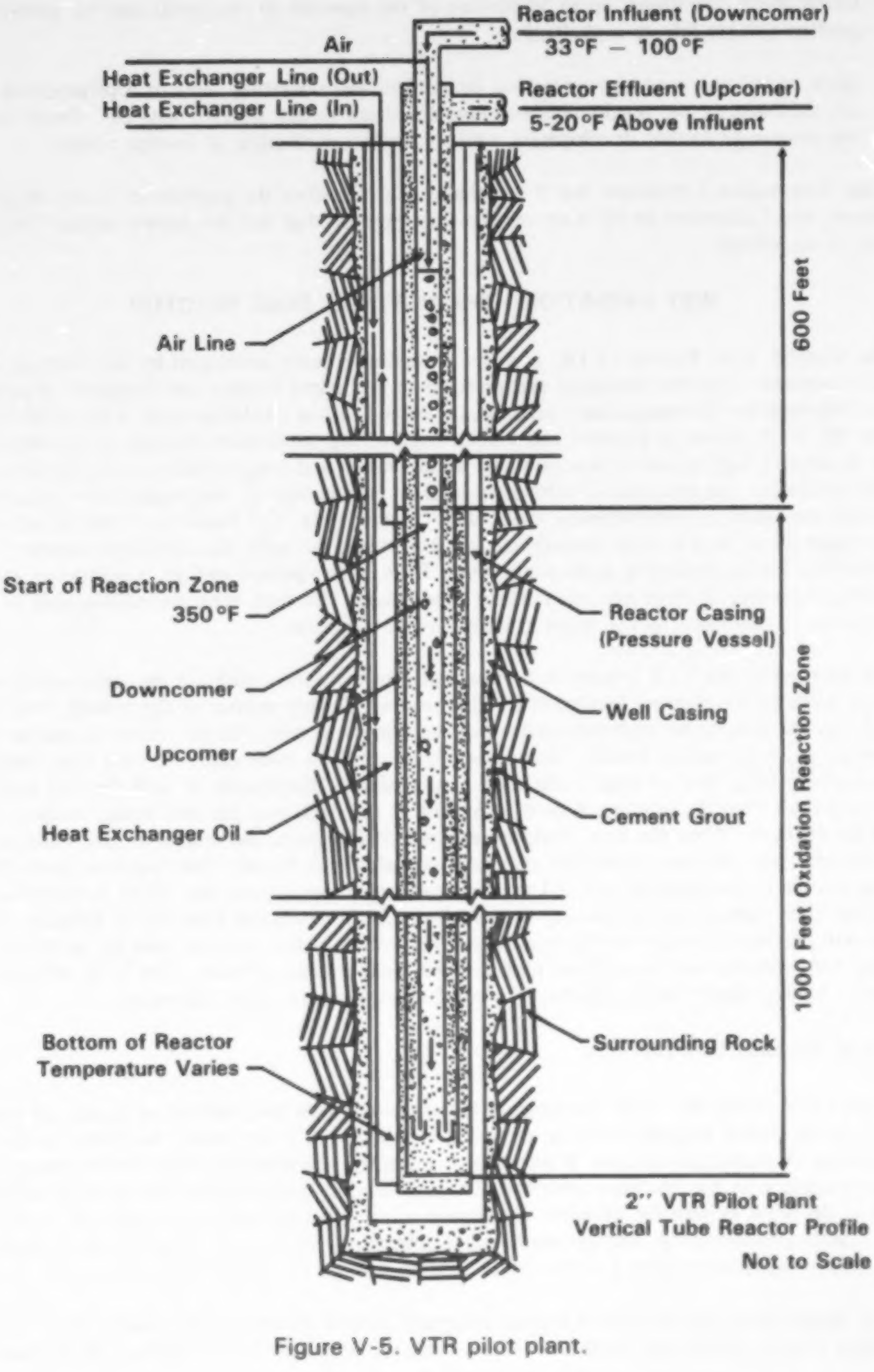
Reactor Influent (Downcomer)
33°F – 100°F
Air
Heat Exchanger Line (Out)
Heat Exchanger Line (In)
Reactor Effluent (Upcomer)
5-20°F Above Influent
600 Feet
Air Line
Start of Reaction Zone
350°F
Reactor Casing
(Pressure Vessel)
Downcomer
Well Casing
Upcomer
Heat Exchanger Oil
Cement Grout
1000 Feet Oxidation Reaction Zone
Bottom of Reactor
Temperature Varies
Surrounding Rock
2" VTR Pilot Plant
Vertical Tube Reactor Profile
Not to Scale

Figure V-5. VTR pilot plant.

loss to environment, compressor requirements, and expected energy production. The laboratory batch reactor pilot plant and computer modeling efforts have often proceeded concurrently. The VTR hydrodynamic computer model simulates any steady-state operational configuration of a VTR. Important outputs of the model include percent reduction of COD, net heat energy output, air compressor requirements, and fluid properties such as temperature and pressure profiles in the reactor.

The VTR heat model computes heat loss to the rock as a function of time, an aid in computing the net heat production of a VTR reactor, and a help in designing the most cost-effective reactor insulation system. The VTR carbonate model computes the solubility of calcium carbonate as a function of various input parameters.

Initial research and development (R&D) work on the VTR process used a bench-scale laboratory reactor. The oxygenation and mixing were accomplished by inverting a small tube filled with sludge and air to simulate the fluid dynamics of a full-size reactor. Pressure in the fixed volume was controlled by heating and cooling with external heaters and coolers. Several models of the laboratory batch reactor have been built; the current version is an invaluable tool in the VTR evaluation studies.

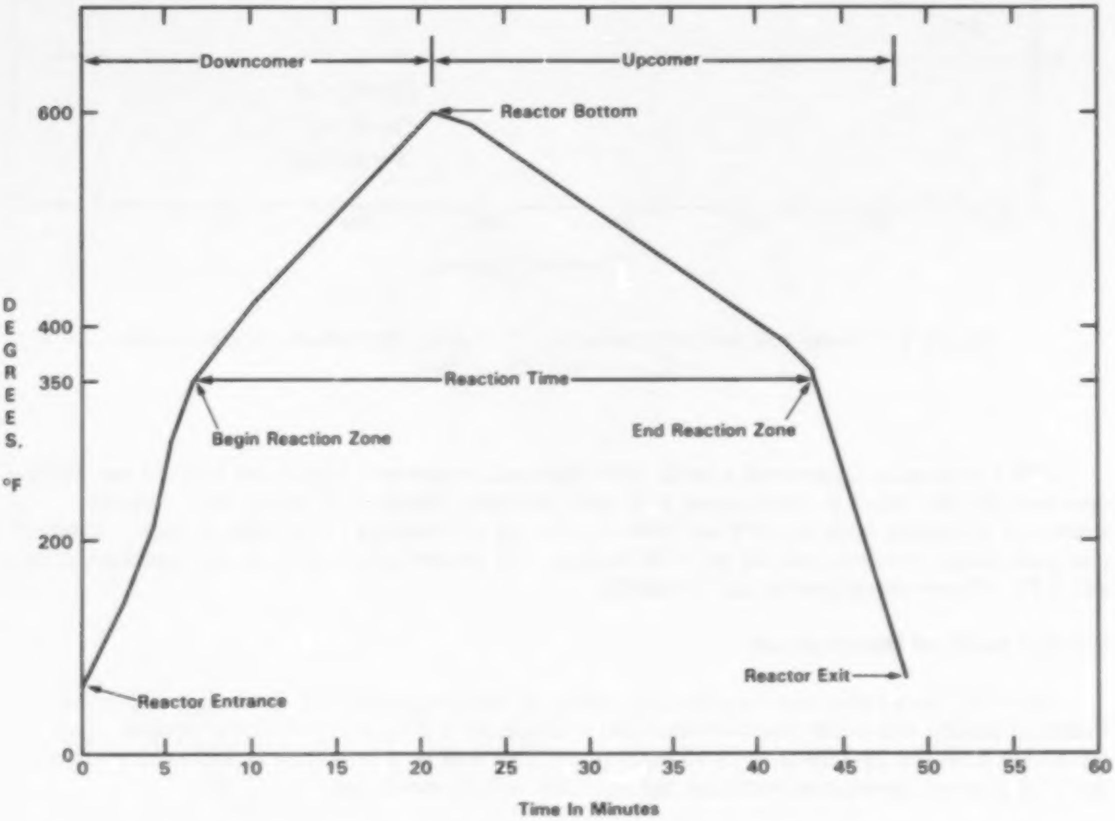

Figure V-6. VTR temperature vs time profile.
(°C = (°F - 32) 5/9).

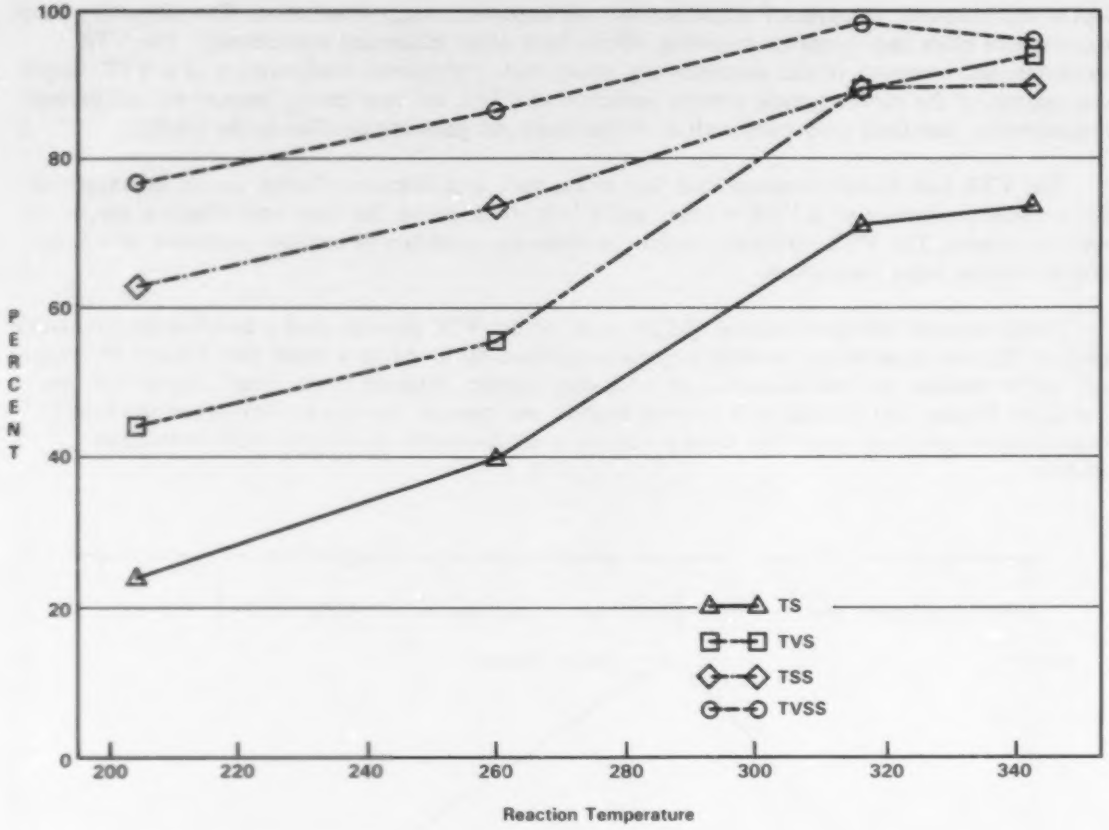

Figure V-7. Average percent reduction in solids, 30-minute reaction time. (°C = (°F - 32) × $^5/_9$).

VTR Corporation constructed a small pilot plant and developed a significant body of test data by operating the pilot plant in combination with both laboratory bench-scale testing and computer studies. A feasibility study in 1979 and 1980 for the city of Montrose, CO, under a Step 1 construction grant study, provided data on the VTR process with respect to construction and operation costs and VTR effluent characteristics and treatability.

Current State of Development

The VTR Corporation has constructed a reactor at the Longmont, CO, municipal wastewater treatment facility within the past few years and will operate it over a 2-year period processing all of the sludge from a 0.22-7.19 m^3/s (5-10 mgd) plant. This will be a prototype facility to demonstrate the VTR process; appropriate technical and cost data will be monitored.

Operational data for the VTR pilot plant are presented in Figures V-6 through V-8. Figure V-6 shows a profile of the temperature conditions, while Figures V-7 and V-8 illustrate solids' destruction at 30- and 60-minute reaction times. Table V-3 summarizes the solids' destruction data.

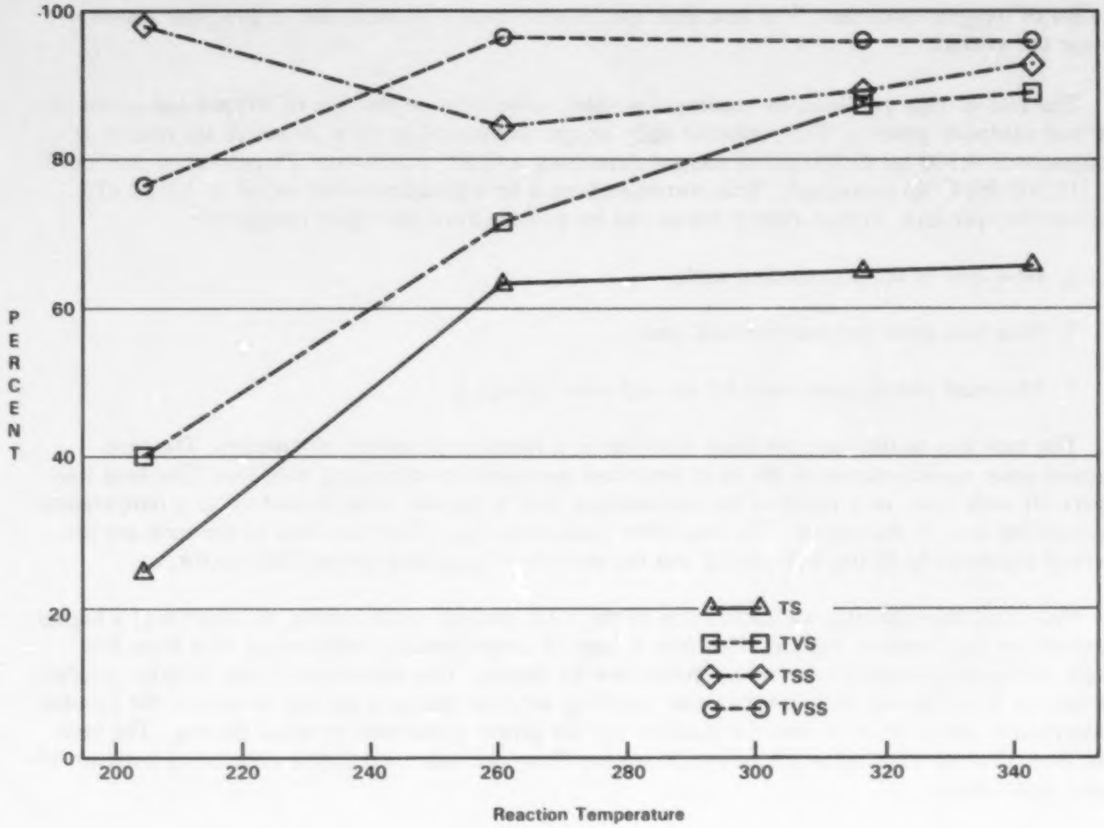

Figure V-8. Average percent reduction in solids, 60-minute reaction time.
(°C = (°F - 32) $^5/_9$).

Table V-3. *Average percent reductions of solid parameters for sludges.*

Temperature	30-Minute Detention				60-Minute Detention			
	TS	TVS	TSS	TVSS	TS	TVS	TSS	TVSS
240°C (400°F)	24	44	63	77	25	40	98	77
260°C (500°F)	40	56	74	87	64	72	85	97
316°C (600°F)	72	90	90	99	66	88	90	97
343°C (650°F)	74	94	90	96	66	89	93	96

Energy Considerations

A properly designed VTR wet oxidation process has the potential to produce more energy than it consumes. As the organic waste is oxidized, heat is released at a rate of about 14,000 kJ/kg (6,000

Btu/lb) of oxygen consumed. The heat produced is recovered efficiently due to low heat losses within the system.

The rate of heat produced by oxidation is solely dependent on the rate of oxygen consumed in the wet oxidation process. The projected daily oxygen consumption for a 20 cm (8 in) reactor at Longmont is 4,300 kg (9,500 lb) of oxygen (assuming a COD reduction of 75 percent of the 5,675 kg [12,500 lb] COD processed). This corresponds to a heat production rate of 60 × 10^6 kJ (57 million Btu) per day. System energy losses can be broken down into three categories:

1. Heat loss to the surrounding rock,

2. Heat loss from thermal washout, and

3. Electrical energy consumed for air and water pumping.

The heat loss to the rock has been modeled as a function of several parameters. The time elapsed since reactor startup is the most important parameter in estimating heat loss. The heat loss tapers off with time, as a result of the surrounding well formation being heated up to a temperature approaching that of the reactor. The two other parameters that affect heat loss to the rock are the thermal conductivity of the well casing and the amount of insulation around the reactor.

Heat loss from thermal washout is due to the VTR process steam exiting the reactor at a higher temperature than when it entered. This loss is kept to a minimum by transferring heat from the warm up-flowing stream to the cooler down-flowing stream. This recuperative heat transfer insulates the reactor from the top hole environment, enabling the heat recovery system to control the process temperatures and to recover heat for possible use for power generation or space heating. The heat loss from thermal washout is a function of reactor flow rate and temperature differential between effluent and influent.

Electrical energy consumption is primarily used for compressing air and pumping reactor influent. The operating conditions used in computing the 20 cm (8 in) reactor's electrical energy demands assume 18,160 kg (40,000 lb) of air (4,300 kg [9,500 lb] of oxygen) injected at 10 kg/cm^2 (150 psig) and an influent flow rate of 6 l/s (100 gpm) injected at 10 kg/cm^2 (150 psig).

COMBUSTION — THE HYPERION ENERGY RECOVERY SYSTEM

Sludge that has been dried can serve as a useful fuel. Indeed, dried sludge is similar in fuel value to lower grade coals, peat, refuse, and other biomass materials. Just as refuse can be processed into refuse-derived fuel (RDF), so sludge can be processed into sludge-derived fuel (SDF) by removal of water prior to combustion. The city of Los Angeles (CLA) is currently implementing a sludge management program for its Hyperion WWTP that includes the processing of sludge to produce SDF and subsequent energy recovery from burning the fuel. The Hyperion Energy Recovery System (HERS) was developed as part of a 5-year facilities planning effort for the Los Angeles/ Orange County metropolitan area (LA/OMA Project). LA/OMA examined all feasible alternatives, recommended HERS as the best management program for the CLA, and completed the environmental documentation. A process diagram for HERS is presented in Figure V-9. Primary sludge and waste-activated sludge will be digested anaerobically, and the digester gas will be used as fuel in a gas turbine, combined-cycle, power system. Digested sludges will be centrifuge-dewatered and then heat-dried using the Carver-Greenfield (C-G) multiple-effect evaporation process. Dried sludge will be used as SDF in a fluidized-bed, gasification/staged, afterburner combustion system with waste heat recovery. Energy will be recovered in the form of electrical power from gas and steam turbine

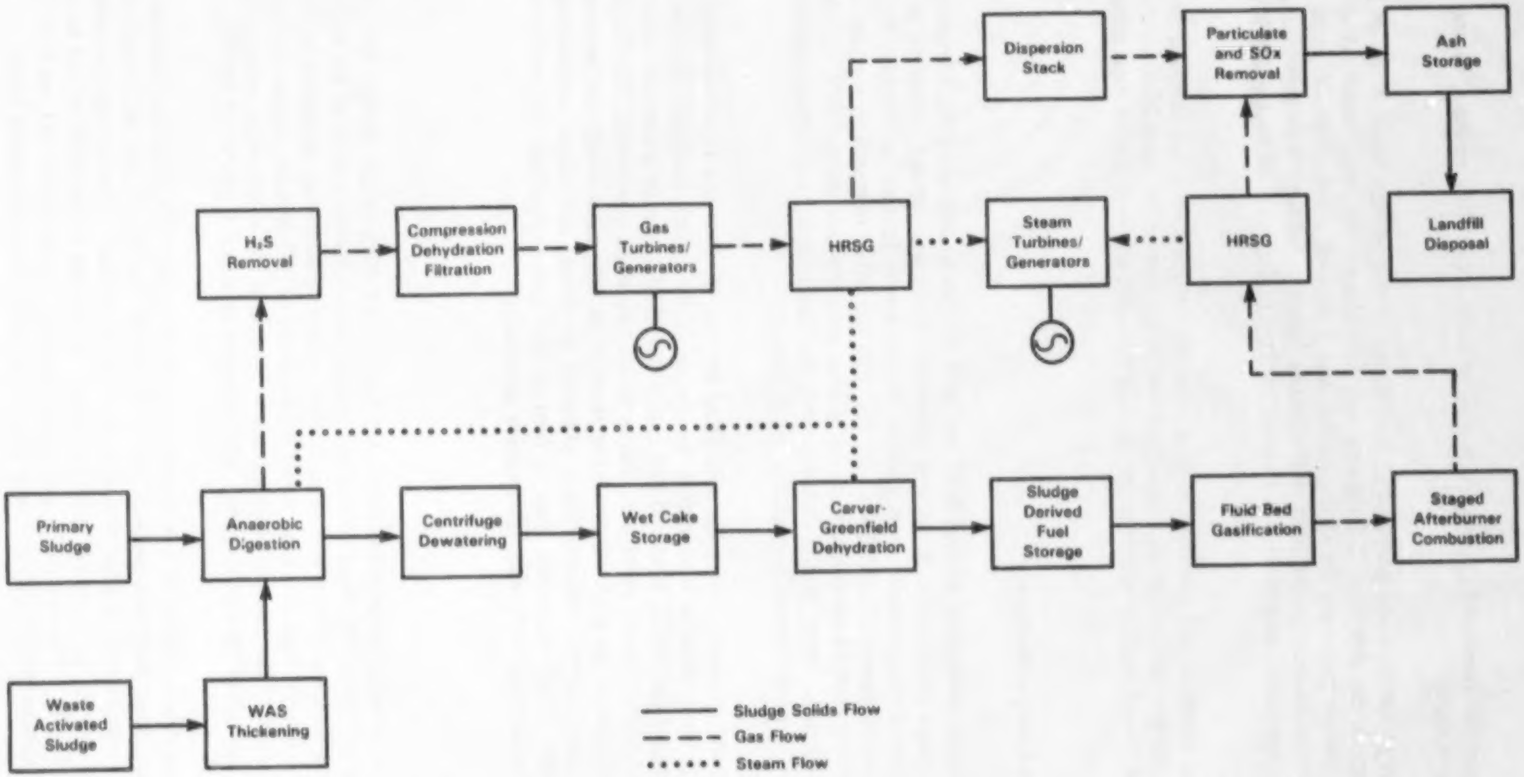
H₂S Removal
Compression Dehydration Filtration
Gas Turbines/ Generators
HRSG
Dispersion Stack
Particulate and SOx Removal
Ash Storage
Steam Turbines/ Generators
HRSG
Landfill Disposal
Primary Sludge
Anaerobic Digestion
Centrifuge Dewatering
Wet Cake Storage
Carver-Greenfield Dehydration
Sludge Derived Fuel Storage
Fluid Bed Gasification
Staged Afterburner Combustion
Waste Activated Sludge
WAS Thickening
Sludge Solids Flow
Gas Flow
Steam Flow

Figure V-9. Schematic HERS for management of sewage sludges with energy recovery from the renewable sludge organics.

generators. Steam from the combined cycle system will be used for heating in the C-G and anaerobic digestion processes.

Intermediate storage facilities are provided at four points in the process train: 1 day of liquid-digested sludge storage in the digesters, 2.2 days of wet cake storage following mechanical dewatering, 3 days of SDF storage following the C-G process, and 3 days of ash storage following thermal processing. The intermediate storage facilities will equalize loadings between unit processes, allow for more steady-state operation, and provide additional backup in the event of temporary process shutdown.

Both the C-G and fluidized-bed combustion processes are designed on a 3/2 modular basis. Three process trains are provided, with each designed for 50 percent of the year 2000 sludge production. The modular design and the intermediate storage facilities are essential to total process train system reliability.

Thermal Processing/Energy Recovery

The LA/OMA Project undertook several field and pilot studies to develop design criteria and air emission factors for sludge combustion. A number of reactor types were tested, including an indirectly heated pyrolytic system, vertical shaft gasifier, rotary hearth furnace, and MHF. Of particular importance to development of HERS was the fact that the MHF operated in a stable and predictable manner during starved-air combustion of SDF at temperatures up to 930°C (1,700°F) without evidence of slagging. These studies demonstrated the feasibility of starved-air combustion (gasification) of SDF using commercially available reactor types.

In 1980 the CLA, in conjunction with the consulting firm of Metcalf and Eddy, undertook supplemental analysis to develop detailed information for design of the HERS facilities. Systems considered for HERS included the MHF, fluidized-bed combustor (FBC), stoker waterwall boiler, suspension fired boiler, rotary hearth pyrolyzer, and modular two-stage combustor. The fluidized-bed system was selected because of its prior successful application in municipal sludge incineration, adaptability to a wide range of fuel characteristics, potential for in-bed and staged combustion for control of nitrogen oxide (NOx) formation, ease of feed of SDF and sludge fuel oil, ease of operation, and competitive economics with other combustion alternatives.

Fuel Characteristics

The C-G process is designed to produce about 221 Mg/d (244 dtpd) of dry sludge fuel and 19 Mgd (21 tpd) of sludge oil for a 240 Mgd (265 dtpd) design total. Characteristics of the fuel that influence design of the combustion system and air pollution control systems are presented in Table V-4. The fuel will have a very high adiabatic flame temperature (T) (0 percent excess air) near 1,800°C (3,300°F) because of the low moisture content. Control of the combustion temperature will be necessary to avoid ash softening and slagging, which begins at about 1,100°C (2,100°F).

Fuel-bound sulfur (FBS) is typical of low to moderate sulfur coals. SO_x emission controls will be required, but flue gas desulfurization methods are well proven. However, the fuel-bound nitrogen (FBN) at 4.5 percent is significantly higher than that of most solid fuels. Without special combustion controls and using conventional incineration systems, about 20 percent of the FBN would be expected to be converted to NO_x. This would be equivalent to over 2 tons/day of NO_x as NO^2. In addition, flue gas denitrification systems are not well proven in solid fuel combustion trains.

Table V-4. *Sludge-derived fuel characteristics of the HERS process.*

Heat value (Btu/lb dry)	
Sludge	5,340 Btu/lb dry (HHV)
Oil	18,700
Combined	6,410
Moisture content	1 percent of total weight
Ash content	38 percent of dry weight
Fuel bound nitrogen	4.5 percent of dry weight
Fuel bound sulfur	1.3 percent of dry weight
Ash fusibility	2,100° - 2,200°F initial deformation temperature 2,300 - 2,450°F fluid temperature
Particle size	Powder

1 kJ = 0.948 Btu 1 kg = 2.205 lb °C = (°F - 32) $^5/_9$

Air Emission Tradeoff. Air emission factors for the HERS combustion system are presented in Table V-5. These factors are believed to be achievable in continuous operation. They are based on results of the combustion test program and the expected efficiency of the air pollution control system. The close simulation maintained during scaleup and the flexibility in the full-scale system were considered in developing these factors.

A summary of air emission projections for HERS is presented in Table V-6. Mass emission rates expected under year 2000 conditions are less than the available offsets for all primary air pollutants. Even under year 2000 conditions, HERS expects a net decrease in air pollutant emissions from existing conditions. Reductions are projected to be as much as 329 kg/d (725 lb/d) for NO_x

Table V-5. *Air emission constraints on design of HERS fluidized-bed combustion system (lbs/day).*

	NO_x (as NO_2)	SO_x (as SO_2)	TSP	NMHC (as CH_4)	CO
Existing reciprocating engines using digester gas (to be retired from service)	1,800	660	225	650	1,740
Gas turbine combined cycle system (year 2000 conditions)	680	20	55	25	715
Offsets available for fluidized-bed system	1,120	640	170	625	1,025

* 1 kg = 2.205 lb.

Table V-6. *Air emission balance for HERS (lbs*/day).*

	NO_x (as NO_2)	SO_x (as SO_2)	TSP	NMHC	CO
Available offsets from Table V-5	1,120	640	170	625	1,025
Estimated emissions from thermal processing	395	145	55	20	65
Direct emission reductions	725	495	115	605	960

* 1 kg = 2.205 lb.

and 275 kg/d (605 lb/d) for NMHC. The latter two pollutants are particularly significant, since they are precursors of ozone, the most troublesome pollutant in the South Coast Air Basin.

Combustion Test Program

An extensive fluidized-bed test program was conducted by the CLA in conjunction with Dorr-Oliver, Inc. Objectives of the test program were to develop detailed criteria for design and air emission factors for subsequent air permit applications. Four fuel types were tested: C-G dried sludge in powder form; C-G dried sludge that was pelleted; CLA sludge that had been dried in a conventional indirect heat dryer; and Milorganite, a heat-dried raw sludge. The four fuel types allowed evaluation of a range of fuel characteristics that spanned the range expected with HERS.

Two combustion modes were examined during the test program: incineration and gasification. In the incineration mode, all fuel and both stoichiometric and excess air were introduced into the fluidized bed. In this mode, the reactor was termed a fluidized-bed combustor (FBC). Essentially complete oxidation of the fuel occurred in the fluidized bed, although some overbed burning was observed. In the gasification mode, primary air was introduced to the fluidized bed in substoichiometric amounts. SDF was partially oxidized and gasified to a low kJ (Btu) gas, termed fuel gas. Fuel gas was then combusted with secondary air by one of three different methods: (1) by secondary air addition to the freeboard above the fluidized bed; (2) in a second-stage fluidized bed; and (3) in an afterburner designed for multiple staging of secondary air addition.

Major conclusions and recommendations for the fluidized-bed test program are summarized as follows:

- No significant differences in combustion characteristics or air emission factors were observed for the fuel types tested. High combustion efficiencies and fixed carbon burnout were achieved with all fuel types and without recycle of fly ash at space velocities of about 1 m/s (3 fps).
- NO_x emissions were markedly affected by the method of combustion. Gasification in the FBG with staged afterburner combustion of fuel gas resulted in significantly lower NO_x emissions compared to other combustion modes examined.

- Principal variables affecting NO_x are the method of secondary air staging, residence time between initial and final air input to the afterburner, exhaust gas O_2 content, and afterburner temperature.

- The lowest NO_x emissions were achieved with partial secondary air addition to the FBC freeboard bringing the total oxygen supply to 80 percent of stoichiometric, secondary air addition to the afterburner bringing the total to 100 percent stoichiometric, and excess air addition bringing the final oxygen content between 4 and 6.5 percent by dry volume. Residence time in the afterburner between the secondary and excess air addition should be 2-2.5 seconds.

- SO_x control by limestone addition to the fluidized bed is enhanced by maintaining oxidative conditions in the bed. Conversely, NO_x control is favored by reducing conditions with staged combustion of the fuel gas.

- Particle-size distribution of the fly ash was similar regardless of the fuel type.

- Conditions for effective burnout of CO and hydrocarbons in the afterburners are:

  — A temperature of 930°C (1,700°F)
  — A residual O_2 content above 3 percent
  — A gas residence time of 2 seconds from the point of excess air addition
  — A high level of gas-phase turbulence.

- Analysis of fuel and ash samples indicated that arsenic, beryllium, cadmium, chromium, copper, lead, nickel, selenium, silver, and zinc should be associated with the ash residue after flue gas cooling in the boiler. Only mercury was consistently unaccounted for in the ash residue.

Full-Scale System Design

The pilot combustion program showed that reducing conditions were not compatible with limestone addition to the fluidized bed for SO_x control. Furthermore, the exhaust SO_x concentration necessary to stay within available emission offsets would require a high Ca/S ratio in the bed. On the other hand, available flue gas denitrification processes, such as selective catalytic reduction, are in an early stage of development and are very expensive compared to control of the combustion process itself. Therefore, a decision was made to control NO_x using the gasification/staged afterburner approach.This decision also meant that SO_x would be controlled by a flue gas desulfurization system.

Because all fuel types were effectively combusted, it was decided to burn the C-G product in powder form. Pelletizing offered advantages in fuel conveyance and feeding to the FBC. However, these advantages were outweighed by the projected costs of pelletizing.

A profile of the HERS combustion system is shown in Figure V-10 and a mass balance in Figure V-11. The FBC is designed as a conventional, bubbling bed type with a space velocity of 0.76-0.9 m/s (2.5-3 fps). Temperature in the bed is controlled by regulating the fluidizing air supply. Since the bed is operated in a substoichiometric zone, heat release is proportional to the quantity of oxygen added for combustion. Heat balances indicate that the bed temperature should equilibrate at 954°C (1,750°F) with about 40 percent of TOC (theoretical oxygen for combustion). Under these conditions a bed area of 10.5 m^2 (113 ft^2) is required, equivalent to the 3.7 m (12 ft) diameter shown in Figure V-10.

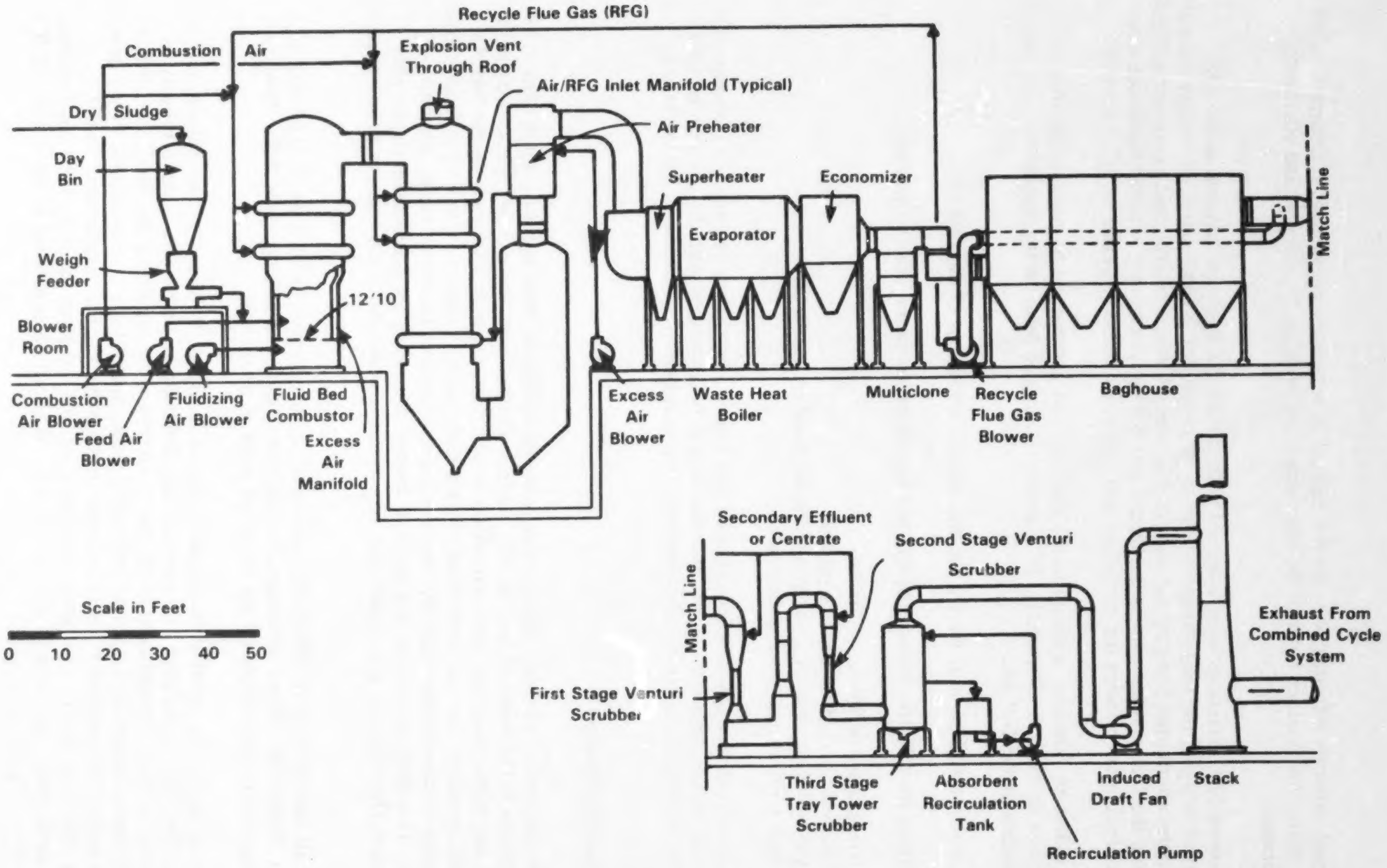
Recycle Flue Gas (RFG)
Combustion Air
Dry Sludge
Day Bin
Weigh Feeder
Blower Room
Combustion Air Blower
Feed Air Blower
Fluidizing Air Blower
Fluid Bed Combustor
Excess Air Manifold
12'10
Explosion Vent Through Roof
Air/RFG Inlet Manifold (Typical)
Air Preheater
Superheater
Evaporator
Economizer
Excess Air Blower
Waste Heat Boiler
Multiclone
Recycle Flue Gas Blower
Baghouse
Match Line
Scale in Feet
0
10
20
30
40
50
Secondary Effluent or Centrate
Second Stage Venturi Scrubber
Match Line
First Stage Venturi Scrubber
Third Stage Tray Tower Scrubber
Absorbent Recirculation Tank
Recirculation Pump
Induced Draft Fan
Stack
Exhaust From Combined Cycle System

Figure V-10. HERS system for fluidized-bed gasification of SDF, staged combustion after-burning, waste heat recovery, and air pollution control.

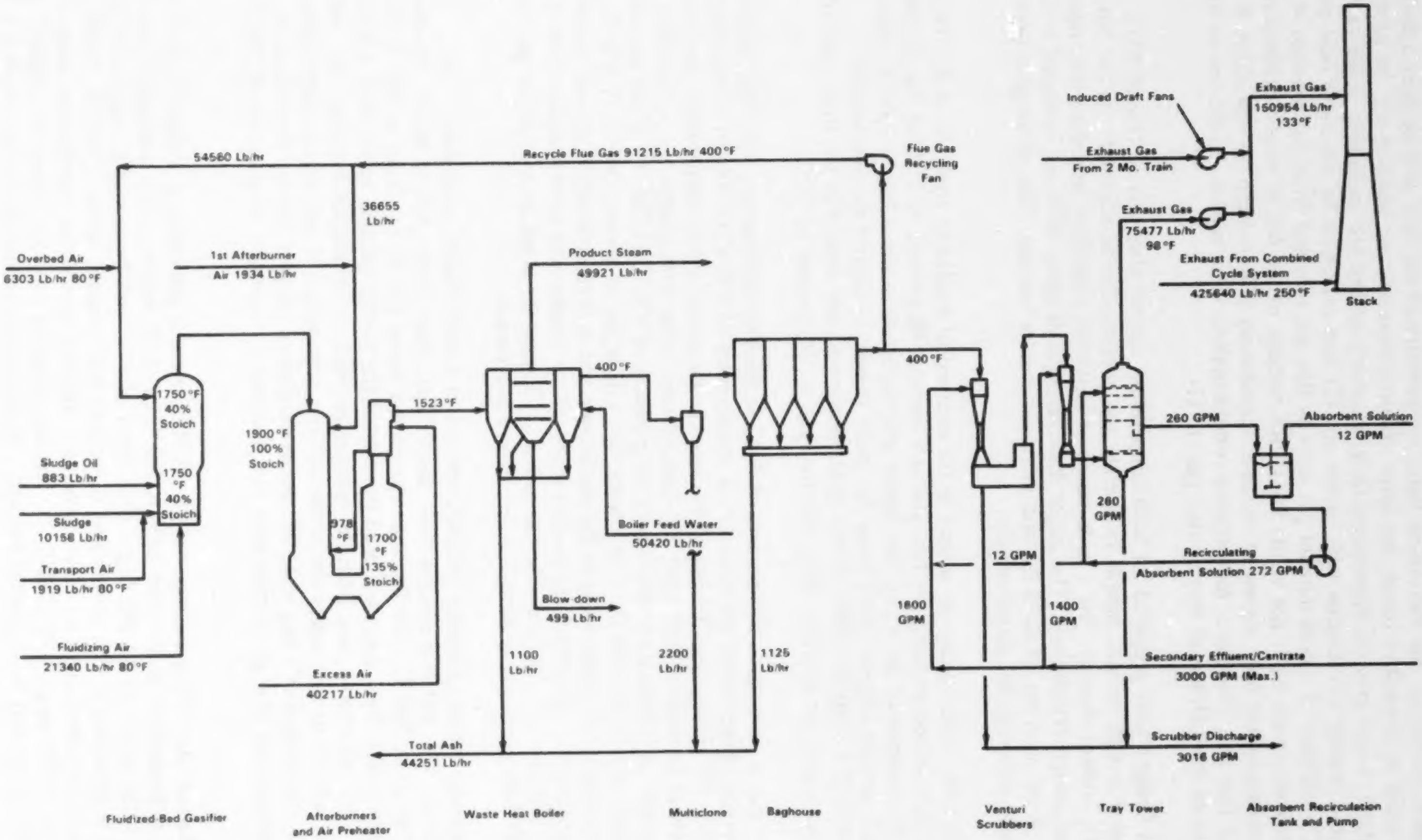
54560 Lb/hr
Recycle Flue Gas 91215 Lb/hr 400°F
Flue Gas Recycling Fan
Induced Draft Fans
Exhaust Gas
150954 Lb/hr
133°F
Exhaust Gas
From 2 Mo. Train
Exhaust Gas
75477 Lb/hr
98°F
Exhaust From Combined Cycle System
425640 Lb/hr 250°F
Stack
36655 Lb/hr
Overbed Air
6303 Lb/hr 80°F
1st Afterburner
Air 1934 Lb/hr
Product Steam
49921 Lb/hr
400°F
400°F
1750°F
40%
Stoich
1523°F
1900°F
100%
Stoich
260 GPM
Absorbent Solution
12 GPM
Sludge Oil
883 Lb/hr
1750
°F
40%
Stoich
Sludge
10158 Lb/hr
978
°F
1700
°F
135%
Stoich
Boiler Feed Water
50420 Lb/hr
260
GPM
Transport Air
1919 Lb/hr 80°F
12 GPM
Recirculating
Absorbent Solution 272 GPM
Blow down
499 Lb/hr
1800
GPM
1400
GPM
Fluidizing Air
21340 Lb/hr 80°F
1100
Lb/hr
2200
Lb/hr
1125
Lb/hr
Secondary Effluent/Centrate
3000 GPM (Max.)
Excess Air
40217 Lb/hr
Total Ash
44251 Lb/hr
Scrubber Discharge
3016 GPM
Fluidized-Bed Gasifier
Afterburners and Air Preheater
Waste Heat Boiler
Multiclone
Baghouse
Venturi Scrubbers
Tray Tower
Absorbent Recirculation Tank and Pump

Figure V-11. Mass and energy balance for one train of the HERS sludge combustion facility operating at year 2000 design load of 120.2 Mg/d (132.5 dtpd) of SDF and sludge oil.

As mentioned previously, the theoretical flame temperature of the SDF will be near 1,800°C (3,300°F) and must be controlled below this level. Substoichiometric air addition will be used in the fluidized bed itself. Three primary approaches to temperature control are applicable in the remainder of the combustion system: (1) dilution with excess air, (2) heat extraction by means of heat transfer surfaces, and (3) addition of a cool dilutant gas such as flue gas recycled from downstream of the boiler. Dilution with excess air is not viable for HERS because of the use of staged combustion and because NO_x emissions had been shown to increase dramatically with oxygen content above 8 percent in the final flue gas. Therefore, temperature control options were reduced to the use of heat transfer surfaces or the addition of recycle flue gas (RFG).

Conceptual designs were prepared for both temperature control alternatives. Use of RFG was selected because it is well proven, simple to operate and control, can be adjusted "on the run," is an effective NO_x control strategy, has a wide range of turndown capability, and does not require extremely accurate design calculations. The major disadvantages of using RFG are increased energy usage because of the need for an RFG fan and increased reactor volume. The advantages were judged to significantly outweigh the disadvantages.

The first addition of secondary air occurs in the overbed or freeboard zone above the fluidized bed. Sufficient O_2 is added to bring the fuel gas to a nominal 80 percent of TOC in the overbed. Flue gas from downstream of the waste heat boiler and baghouse is about 200°C (400°F) and contains a nominal 5 percent oxygen. RFG from this point is used to control the combustion temperature to 954°C (1,750°F). RFG is also used for temperature control in the first stage afterburner, where secondary air addition brings the fuel gas to 100 percent of TOC.

Because the gas is brought to 100 percent of TOC in the first afterburner, very little fuel value is likely at the point where excess air is added. A temperature of 930°C (1,700°F) is required in the second afterburner for burnout of CO and hydrocarbons. To maintain this temperature, the excess air will be preheated to about 500°C (950°F). Temperature in the first afterburner is regulated by RFG addition, which is controlled to maintain a temperature of 930°C (1,700°F) in the second afterburner. Heat balances indicate that the first afterburner will adjust to about 1,040°C (1,900°F). This is the maximum temperature maintained in the combustor and is several hundred degrees below the ash softening temperature. Nevertheless, a vertical downflow reactor was used because of the higher gas temperature and concern over possible ash softening. Excess air is added to cool the gas back to 930°C (1,700°F) before the gas is turned in the second afterburner.

The heat recovery steam generator (HRSG) consists of a superheater, evaporator, and economizer sections. The unit is a straight flow, nonbaffled, three drum, A-type boiler. Feedwater will be received at about 160°C (320°F), and superheated steam will be produced at 400°C/43 kg/cm^2 (750°F/620 psig). Bare tubes are used throughout the HRSG because of the high ash content of the flue gas. Flue gas temperature from the economizer will be maintained between 190° and 200°C (380° and 400°F) to stay safely above the sulfuric acid dewpoint and within temperature limits imposed by the baghouse's bag material. Boiler feedwater temperature can be reduced if necessary to modulate exit flue gas temperature and maintain a maximum temperature of 200°C (400°F).

Energy Balance. An energy balance for the HERS system is presented in Figure V-12. Projected digester gas production in the year 2000 is 2,050 l/s (6.25 million scfd), equivalent to 4.28×10^9 kJ/d (4,060 MBtu/day). About 292 Mg/d (265 dtpd) of SDF will be produced, equivalent to 3.6×10^9 kJ/d (3,400 MBtu/day). The gas turbine generators will produce about 12.6 MW. Each gas turbine will exhaust to a heat recovery steam generator (HRSG), producing superheated steam at a nominal 76 kg/cm^2 (1100 psig), 430°C (807°F), and low pressure saturated steam at 2 kg/cm^2 (30 psig). Superheated steam will be expanded through a backpressure turbine producing about 2.4 MW.

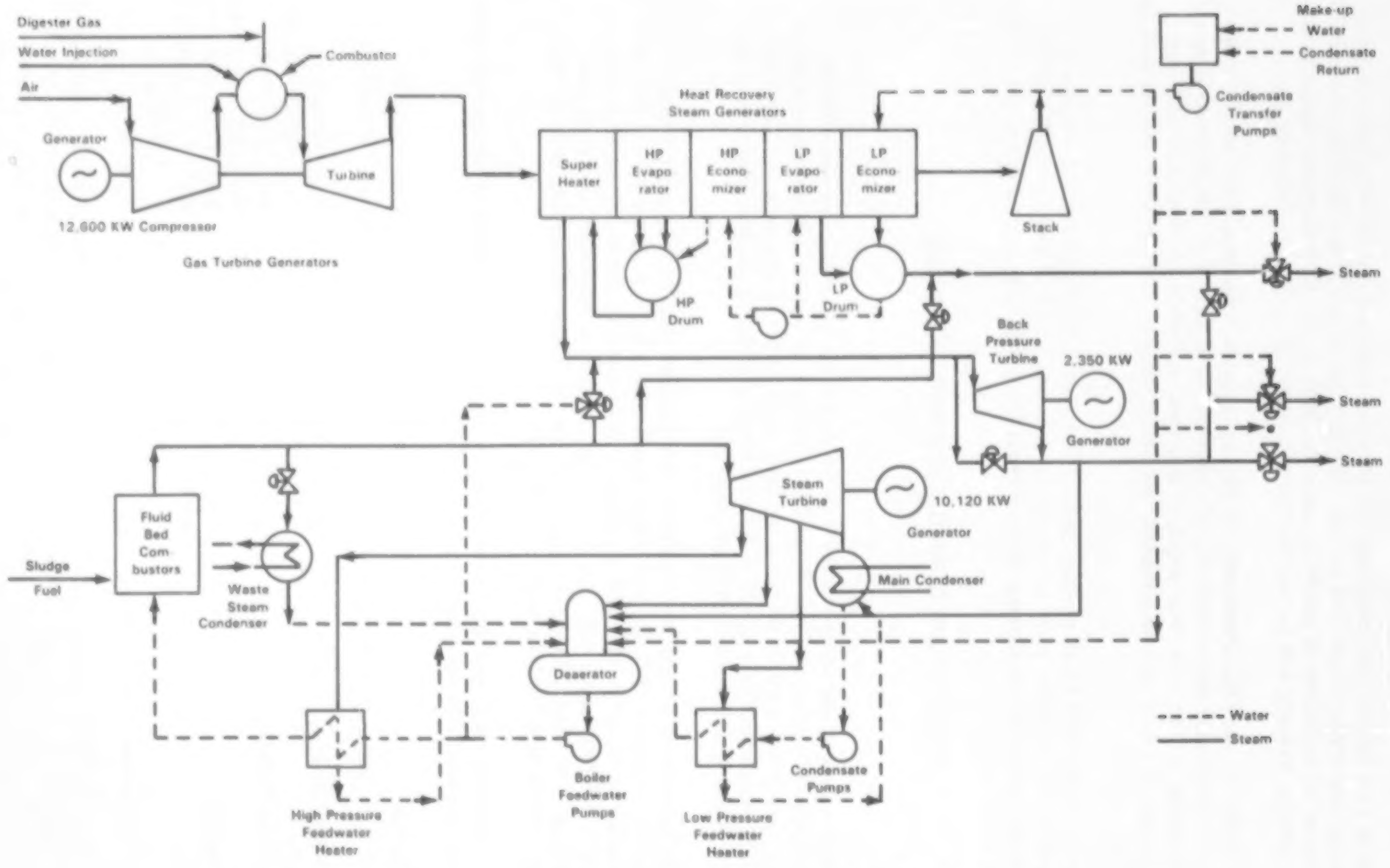
Digester Gas
Water Injection
Air
Combustor
Generator
12,600 KW Compressor
Turbine
Gas Turbine Generators
Heat Recovery Steam Generators
Super Heater
HP Evapo rator
HP Econo mizer
LP Evapo rator
LP Econo mizer
HP Drum
LP Drum
Stack
Make-up Water
Condensate Return
Condensate Transfer Pumps
Steam
Steam
Steam
Back Pressure Turbine
2,350 KW
Generator
Steam Turbine
10,120 KW
Generator
Main Condenser
Sludge
Fuel
Fluid Bed Com bustors
Waste Steam Condenser
Deaerator
Boiler Feedwater Pumps
High Pressure Feedwater Heater
Low Pressure Feedwater Heater
Condensate Pumps
Water
Steam

Figure V-12. Process diagram for the energy recovery elements of the HERS project. Energy production estimates are for year 2000 conditions with 177,000 m³/d (6.25 million scfd) of digester gas (4,280 kJ/d [4,060 Btu/d]) and 292 Mgd (265 dtpd) of SDF (3.5 × 10^9 kJ/d [3,400 million Btu/day]).

Expanded steam at 11.4 kg/cm² (165 psig) and low pressure steam will satisfy all process demands for digester heating and drying in the C-G process. Digester gas serves as the base fuel in the HERS energy cycle because of its history of reliable production. Most of the HTP electrical requirements and all process heating demands will be met through the combined-cycle use of digester gas.

Waste heat boilers in the FBG/afterburner combustion trains will produce about 45,000 kg/hr (100,000 lb/hr) of superheated steam at 400°C /43 kg/cm² (750°F/620 psig). The steam will be expanded in a condensing turbine with three stages of automatic extraction for deaeration and feedwater heating. About 10.1 MW will be produced. Secondary effluent from the HTP will be used for condenser cooling.

With the above fuels, HERS will produce about 25 MW of electrical power and all process steam requirements. The Hyperion plant is expected to consume a total of about 15 MW for both wastewater treatment and solids processing, leaving about 10 MW of cogenerated power for export to the electrical utility grid.

STARVED-AIR COMBUSTION AND PYROLYSIS

United States

The mid-1970s saw a strong interest develop in the possibility of using more fuel-efficient methods of combusting sludge solids. The Federal Government encouraged furnace manufacturers, design engineers, and owner agencies to prove out their innovative concepts such as "starved-air" or substoichiometric burning. This resulted in demonstration projects by Nichols Engineering and Research in New Jersey and Envirotech-BSP in California.

A first-time, full-scale plant combustion facility was designed then by Alexander Potter Associates/CDM for Arlington, VA, for starved-air combustion (SAC) of sludge solids. The Arlington system started up in early 1984, and a definitive comparison of normal incineration and starved-air mode is currently under way. Another project, located at Allegheny County Sanitary District in Pittsburgh, PA (ALCOSAN), is supposed to use the Zimpro Cyclo Hearth MHF in a starved-air mode. It was scheduled for startup in late 1984.

SAC is not a discrete chemistry, but rather a part of the spectrum of ratios of sludge fuel value to oxygen that are possible. The spectrum ranges as follows:

Terminology	Percent Excess Air	Used in USA
"Hot sludge" incineration	100 to 200	Yes - several
Normal incineration	50 to 150	Yes - most common
Minimized air (ICFAR mode)	20 to 60	Yes - a few
No excess air	zero	No - theoretical only
Starved-air combustion	−20 to −60	Yes - prototypes only
Pyrolysis (true)	−90 to −100	No - requires indirect heating

It must be noted that SAC and pyrolysis require a supplemental oxidation step, or "afterburn," to complete the combustion of the fuel factors in the off-gas. These can include carbon monoxide, hydrogen, lower hydrocarbons, carbonyls such as malodorous aldehydes, and partially oxidized sulfur and nitrogen compounds. This secondary combustion would be done in a separate chamber where excess air conditions exist, and where the gases may become very much hotter, possibly up to 1,100 °C (2,000 °F), depending on the excess air ratio provided. Thus the total process of SAC or pyrolysis would produce a gas volume of combustion products comparable to normal incineration, but the following major advantages accrue to SAC: (1) gas volume flow rate, and thus ash particle entrainment, is much less in the primary chamber; (2) the secondary oxidation enhances complete destruction of organics, assuring an odor-free exhaust of zero opacity; and (3) creation of hexavalent chromium species is minimized, making the ash more acceptable.

SAC may also be called "two-stage combustion" because there are two distinct zones of oxidation. In excess-air incineration, these two blend in the furnace and there is no clear line of demarcation, although a few MHFs have been built with special gas handling systems that permit a separation of these zones.

MHFs have been built with a feature called an "afterburner." This may be either the top ("zero") hearth, which does not receive feed and is built to maximize detention time, or a separate chamber beside the furnace. These furnaces do use excess air in the sludge solids burn zone, however, and the supplemental holding chamber is only to assure residual burnout and perhaps smoke control, rather than being an integral part of the thermodynamic design as in SAC.

SAC is not a new art. The processing of wood waste, accomplished in Dutch ovens, is actually a two-stage process. SAC has been carried out for many years in several applications of multiple-hearth technology, the most common being the production of barbeque charcoal from biomass such as agricultural wastes.

Perhaps the easiest way to understand SAC is with the aid of graphs. Figure V-13 depicts a plot of theoretical temperature of products of combustion versus percent stoichiometric air for a typical municipal sludge. These temperatures are purely theoretical and no inference is made that any combustion would take place below some minimum temperature—760 °C (1,400 °F). The gradually sloping line at the left is intended to represent the evaporation of moisture and terminates at an arbitrary temperature of 100 °C (212 °F). In the substoichiometric region (less than 100 percent stoichiometric air), straight lines have been used to connect known points. In actual practice these will not be straight, but this assumption is sufficiently accurate for equipment sizing. The temperature at 100 percent stoichiometric and greater can be calculated very accurately. As seen on this graph, in the substoichiometric region, temperature increases with increasing air, while in the excess air region (greater than 100 percent stoichiometric), temperature decreases with increasing air. The theoretical temperature of the products of combustion depicted in this curve never reaches 760 °C (1,400 °F) at any point in the excess air region and therefore does not represent a viable system.

To reach a minimum of 760 °C (1,400 °F) at the final exit condition of 6.0 percent oxygen (40 percent excess air), auxiliary fuel must be added to the system. A "First Law" analysis will indicate that the quantity of auxiliary fuel required will be the same whether the fuel is added to the first or second stage. Figure V-14 depicts two different "combustion paths," one for the fuel added to the primary chamber and one for the fuel added to the secondary chamber (afterburner). With fuel added to the primary chamber, the exhaust temperature, and hence the average hearth temperature, is higher. This will increase the capacity kg/m^2/hr (lb/ft^2/hr) of the MHF. Figure V-15 indicates that if the TS of the sludge is increased to 33 percent, the sludge will be autogenous under the afterburner exhaust conditions shown (760 °C [1,400 °F] and 140 percent stoichiometric [40 percent excess air]). Figure V-16 depicts a typical TCS, which again will be autogenous but additionally allows the use of a higher temperature or increased excess air in the afterburner. Figure V-17 depicts a "hot" sludge, which would be a TCS that has undergone some enhanced dewatering technique such as belt press. Although operation at the 1,300 °C (2,400 °F) temperature indicated would undoubtedly cause some slagging problems, the opportunity for high-temperature, autogenous operation is certainly present.

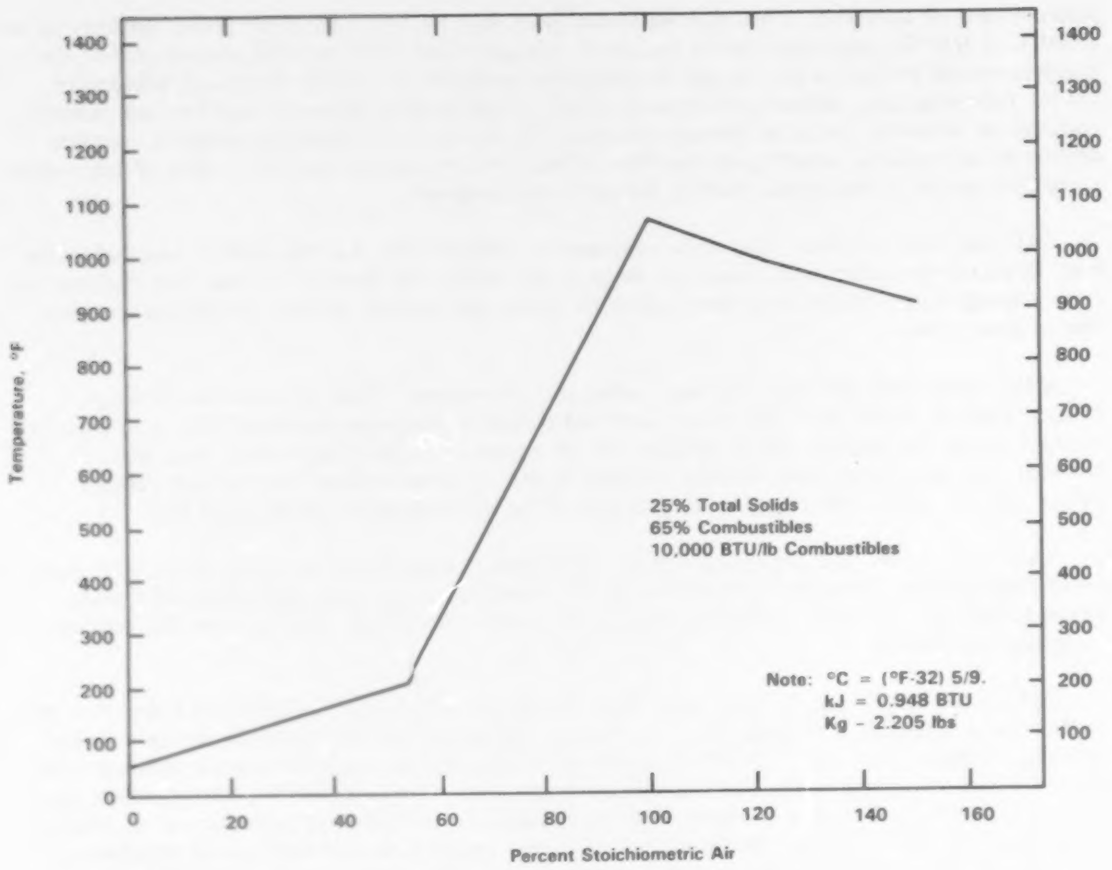

Figure V-13. Plot of theoretical temperature of products of combustion vs. percent stoichiometric air.

Germany

In addition to the proven waste incineration technologies, there has been increased work on new thermal waste treatment processes, among them pure pyrolysis and SAC. These processes should make possible facilities that function cost effectively in areas where there are low rates of throughput, thereby making possible their installation in smaller service districts. Further, they should make possible the recovery of energy and/or raw materials and should also be flexible enough to accept changing combinations of types of wastes. This means that the new facilities must be able to treat not only household waste, but also other forms of wastes such as wastewater sludge, and should cause minimal environmental impact.

Pyrolysis means the decomposition of solid or liquid organic materials at high temperatures (400° - 700°C) in the absence of air. Other terms for this process are degasification, carbonization, and dry distillation. Wood, peat, coal, and oil shale have been pyrolized in the past, producing a carbon-rich coked residue and a hydrocarbon-rich product oil and gas. In principle, organic wastes or components of waste such as rubber, plastics, paper, textiles, oils, fats, and similar materials are suitable for pyrolysis. At present two prototypes are under construction in West Germany:

- Goldshofe near Aalen: Pyrolysis of household waste and wastewater sludge in a rotary kiln, using the Kiener process, with a throughput of 3 Mg/h (2.7 t/h).

- Gunzburg/Donau: Pyrolysis of household waste and wastewater sludge in a rotary kiln, using the Babcock-Krauss Maffei process, with a throughput of 2-3 Mg/h (1.9 - 2.7 t/h).

Kiener Process. In the Kiener process, the wastes are transported from a silo into the rotary kiln after the household wastes are shredded and mixed with wastewater sludge. Inside the kiln, the wastes are degasified at temperatures of about 450°C. The residues, which consist of inorganic matter (80-90 percent) and pure carbon (10-20 percent) are discharged via a dry lock and stored on a landfill site. The pyrolytic gases are then partially combusted in a cracking generator, reaching temperatures of about 1,100° - 1,200°C (2,010°-2,190°F) and producing a gas consisting mainly of methane, hydrogen, carbon monoxide, carbon dioxide, nitrogen, and water vapor.

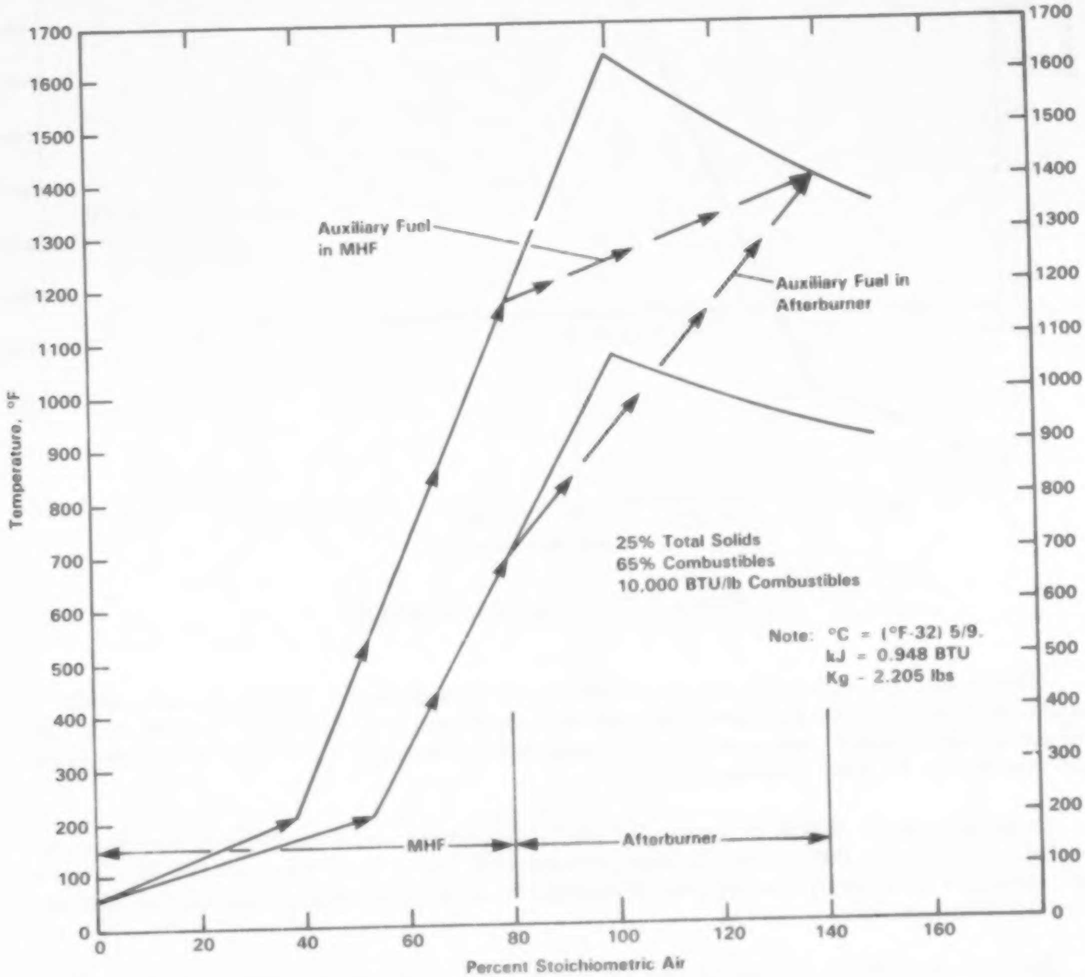

Figure V-14. Two different combustion paths.

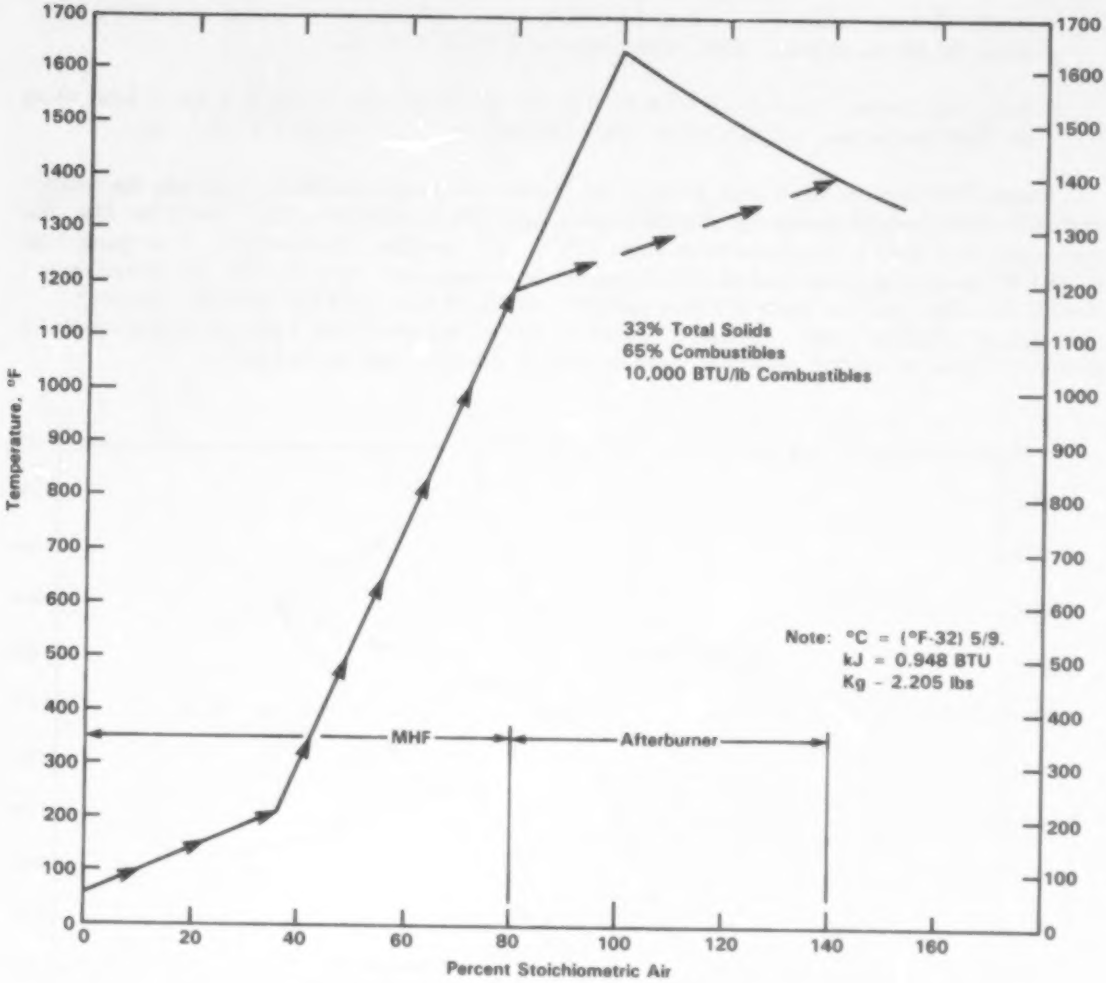

Figure V-15. Autogenous sludge.

After further dust separation and gas scrubbing, the final product is burned in a gas engine coupled with an electricity generator. The exhaust from the gas engine serves to heat the rotary kiln. The gas scrubbing water, contaminated with predominantly inorganic material, is first cleaned and then emitted into the main drainage channel.

Babcock-Krauss Maffei Process. The plant in Gunzburg, which is currently shut down, is capable of handling 22,000 Mg/yr (24,500 t/yr) household waste, 5,400 Mg/yr (6,000 t/yr) commercial waste, and 4,000 Mg/yr (4,500 t/yr) of wastewater sludge containing chromium, thus serving about 100,000 inhabitants.

The main steps of the process are as follows: the waste is fed into the rotary kiln, where it is degasified at 400° - 450°C (750° - 840°F),simultaneously binding the hydrogen chloride and hydrogen fluoride that evolves by adding lime into the kiln. The residues are quenched and dis-

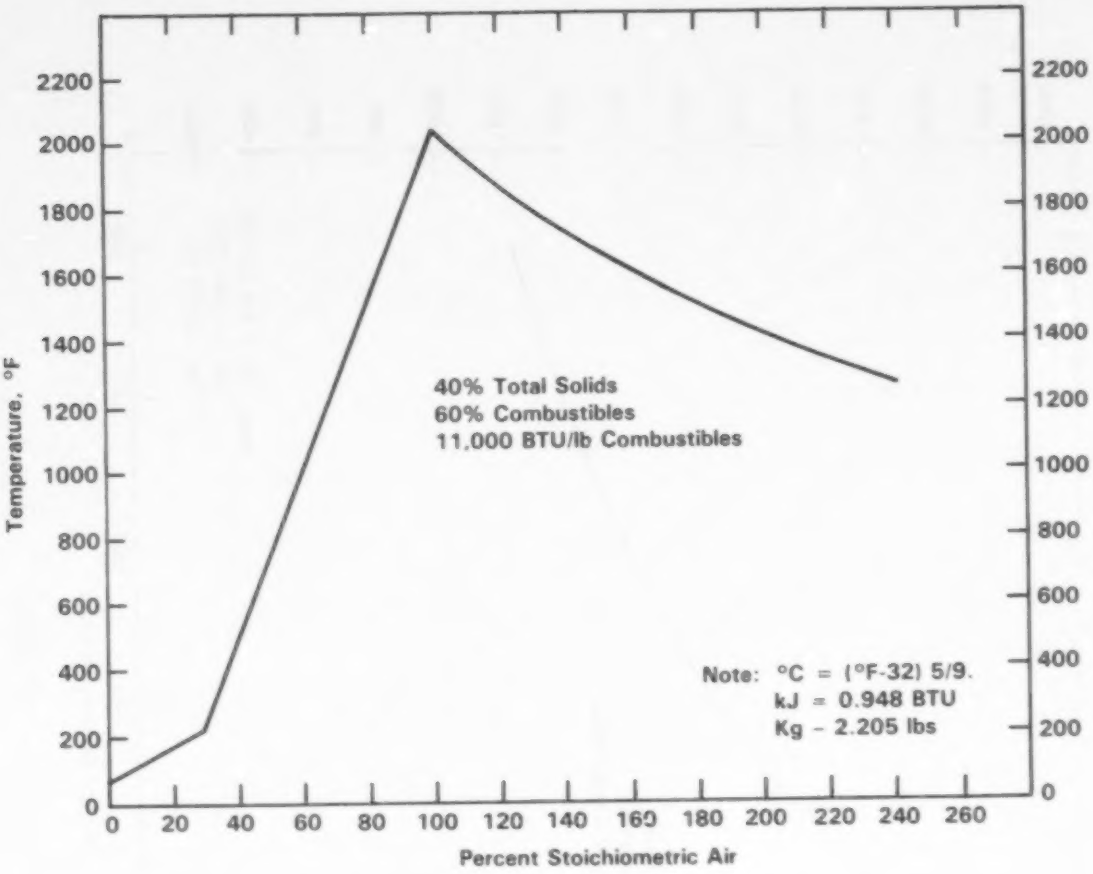

Figure V-16. A typical thermally conditioned sludge.

charged wet. The gases are passed through heated cyclones and subsequently incinerated in a combustion chamber with 30-40 percent excess air. Some of the hot flue gases are returned to heat the kiln. the balance being used for steam production in a waste heat boiler and for generation of electricity.

An advantage of low-temperature pyrolysis is that for the first time the process permits the thermal disposal of wastes such as wastewater sludge and industrial sludges that contain heavy metals. This advantage may become more important in the future. For example, low-temperature pyrolysis ensures that wastes containing chromium III are not oxidized to chromium IV, which is highly water soluble; thus the toxic metals remain in the solid residues and are not released to the environment.

Japan

In the mid-1970s, the presence of hexavalent chromium compounds in ash from furnaces burning lime-conditioned sludge was pointed out as a serious environmental problem. Trivalent chromium as a cation (chromic ion), used in the leather tanning industry, among others, was found to be converted to chromate anion in the high temperatures of conventional incineration. The chromate was

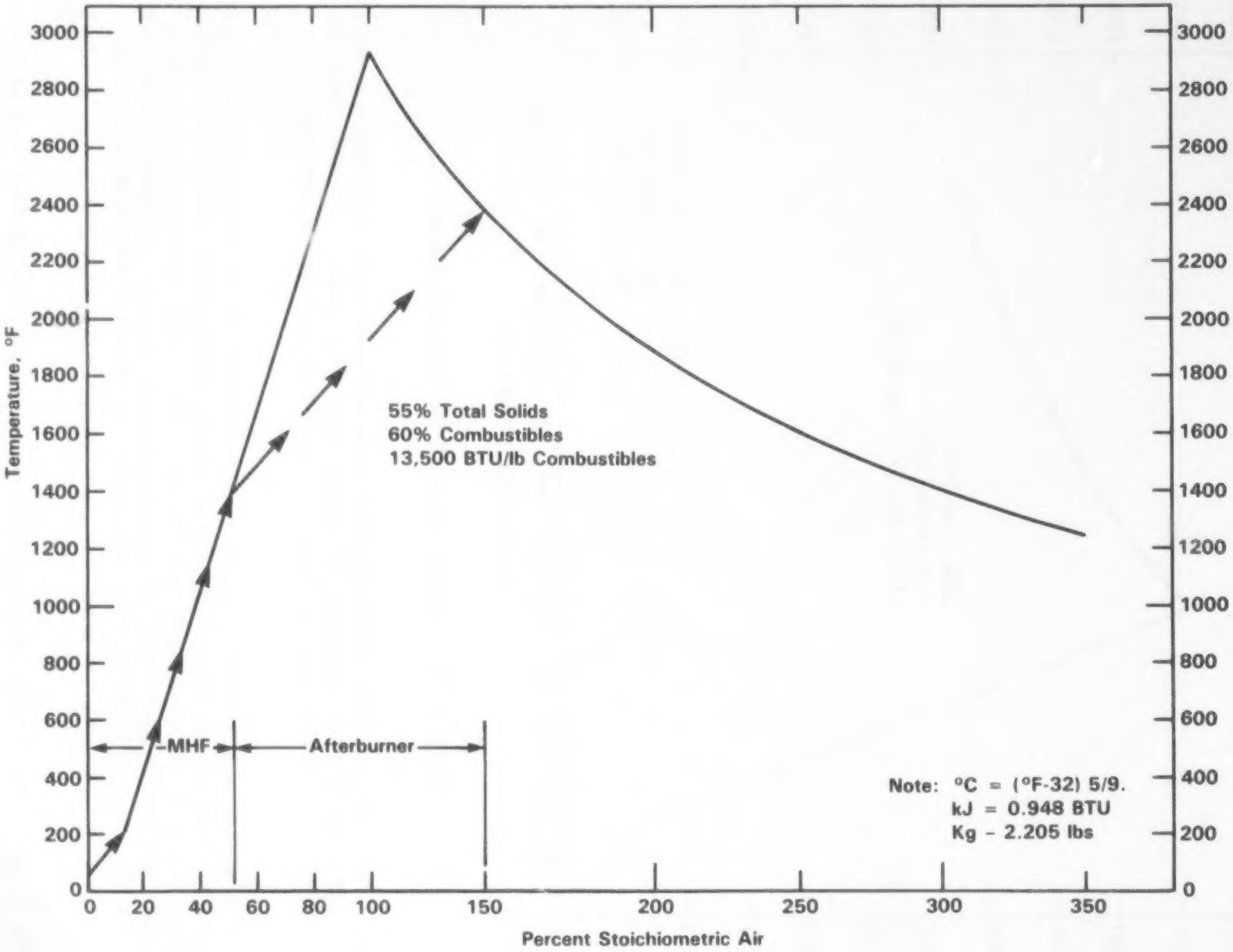

Figure V-17. A "hot sludge."

known to be toxic in aqueous environments, and, in fact, was a commonly used component in biocides for algae control in cooling towers.

For the prevention of chromate formation and for potential fuel cost savings, these new methods of combustion were investigated in Japan. Two types of processes have been developed: drying-pyrolysis and SAC.

The pyrolysis system uses an indirect-type steam dryer, MHF, and waste heat recovery boiler. It is considered suitable for loadings up to 100 tons per day.

The SAC system is applied in a modified MHF, but the ratio of excess air to combustibles in the cake is only 10-30 percent. One or two hearths are operated in the reducing condition to prevent production of hexavalent chromium.

Gas recirculation is used to compensate for the lower velocity that the lesser air volume would create that would adversely affect the drying process. This is applied only in the upper hearths, where it does not result in ash entrainment.

The number of such systems has been increasing and they appear to be the preferred future technology in Japan whenever the chromium content of the sludge causes concern.

COMBINED MH/FB PROCESS

An interesting combination of design features is represented by a configuration developed by Lurgi in Germany, installed in Frankfurt (the home of Lurgi headquarters), and adopted in Japan in a city in the Hygo Prefecture. The design consists of a multiple-hearth (MH) system mounted on top of a fluidized-bed (FB) system.

In Frankfurt, the units of this type are designed to handle 10 tons per hour of filter cake at 30 percent solids. The MH portion has no burners and acts merely as a stirring and transport device to expose the sludge cake to part of the hot gases from the FB portion. The sludge is heated before centrifuging, to increase dewatering performance. The odorized gases cooled by the drying process are recycled into the combustion zone below. This method of operation is advantageous in locations such as Germany, where the off-gas must leave the combustion zone at 800°C (1,470°F), yet a minimum of excess air in combustion is desirable for thermal economy.

Advantages cited for this configuration include (1) smaller diameter for the windbox and FB, since sizing is not controlled by drying rate; (2) low alloy, and thus less costly, rabbling system in the MH portion; (3) requirement for only a single burner; (4) steadier in operation and thus easier to control; and (5) the action of MH as a distributor and feed-rate controller to the FB portion.

A Selected Plant, Frankfurt (FRG)

The increasing amount of sludges and other residues originating from the new wastewater treatment plants in and around the city of Frankfurt no longer allowed their composting or landfilling. The municipality therefore decided to build a new wastewater sludge incinerator of the Lurgi MH/FB design to handle the wastewater sludge derived from about 2.2 million inhabitants. This incinerator went into operation in 1981. The investment was about 80 million DM ($32 million). The following waste amounts are treated:

330 m^3/d wastewater sludge
20 m^3/d screenings
25 m^3/d sand from wastewater pipelines
10 m^3/d oil and grease   10 m^3/d oil-containing sand
15 m^3/d grease sludge

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410 m^3/d overall sludges

After storage of the sludge, it is pumped through a heat exchanger for preheating by oil that has been heated to about 240°C (460°F) by the incinerator flue gases. After preheating and addition of fluocculents, the sludge is dewatered in a centrifuge to about 30 percent dry matter. The water goes back to the wastewater plant, while the sludge is conveyed into the combined MH/FB incinerator together with screenings. The incinerators have a capacity of 9 Mg/h (10 t/h) each (30 percent dry matter). Two are in operation with one on standby. After further drying in the five hearths, the sludge falls into the fluidized bed, where it is incinerated at about 800° - 850°C (1,470° - 1,560°F).

Auxiliary heat for startup or hot standby is provided by the incineration of waste oil. Fans provide the air for fluidization and oxidation of the waste. The flue gases leave the incinerator with a temperature of about 850°C (1,560°F). Their sensible heat is used for drying purposes in the MH, heating the heat-exchange oil, preheating of the combustion air, and reheating the flue gases after scrubbing. The remaining 15 percent stays in the flue gases; thus no additional fuel is needed for the incineration of the sludge.

Flue gas cleaning is by electrostatic precipitators. Any harmful components remaining are eliminated in a double-stage washing tower/rotary scrubber before the cleaned gases are released into the atmosphere. This comprehensive flue gas treatment produces satisfactory compliance with the air quality permit, with minimum adverse impact on the surroundings. The scrubbing water is taken from the outlet of the wastewater treatment plant while the polluted scrubbing water is sent back to the wastewater treatment plant.

Investigators have shown that virtually all of the heavy metals are concentrated in the fly ash where they are firmly bound, being extracted neither by rain nor by leachate in a landfill. Therefore, the remaining 50 m^3/d ash is landfilled together with household waste.

MELTING (SLAGGING) FURNACES IN JAPAN

During the past 4 or 5 years, many new methods of wastewater sludge incineration have been announced in Japan, including the use of technology from other countries. The need for economy in energy use, the enactment of much stricter regulations for pollution control, and changes in the properties of the dewatered cakes caused by the use of polymers have prompted the development of these new methods. In Japan, the ultimate target of development is the melting (slagging) furnace, which produces a glassy ash product.

The types of melting furnaces that have come into operation or are now under development include:

- Electric arc furnace,
- Double cylindrical furnace,

- Pulverized fuel furnace,
- Shaft furnace, using coke admix, and
- Tank furnace.

The common requirement of these systems is the need to dry the dewatered cake prior to feeding it into the furnace to minimize the steam and dry it more efficiently.

The only system in operation now at an actual plant is the electric arc furnace in Kawasaki City. Others still in the experimental stage are classified as process development units (PDUs). The electric arc furnace is an adaptation of the type used for melting metal in steel manufacturing and foundry industries. It is not presently considered economical, due to the rapid consumption of electrode rods and electric power. However, the officials of Kawasaki City selected it because it greatly reduced ash volume—a major consideration in view of the dense population of the city and the unavailabilty of land for ash disposal.

A shaft (cupola) furnace using coke mixed with the sludge cake is now under development by Osaka Gas Company, Ltd. This is a vertical cylinder lined with refractory brick. Molten slag is removed at the bottom. Coke is used for its auxiliary fuel value and because it forms a porous bed. The coke and the fairly dry cake, at a moisture content of about 50 percent, are fed alternately into the top of the cupola. One problem with this system is that coke must be used to form the bed even in the case of burning high calorific cake that would burn autogenously; thus energy is wasted.

The double cylindrical furnace applies a film-melting process. It is being developed by two different companies.

The tank furnace is an adaptation of the reverberator used in the glass industry. It can readily be used for melting ash from conventional incinerators.

The pulverized fuel furnace is similar to the cyclonic burner used in electric power generation plants. Both horizontal and vertical types are now under development. The process consists of dryer, crusher, furnace, and gas treatment. The dewatered cake is first dried to a residual moisture of 5-20 percent, then crushed in a hammermill. The particles are fed into the furnace with atomizing air and burned. Ash forms and melts in the combustion chamber.

The final target of these developments is to burn sludge solids without supplemental fuel, melt the ash, and make heavy aggregates for construction materials from the slag, a so-called autogenous melting system. The development activity will continue to verify operating reliability, life of the refractory brick, and ease of operation. It is expected that in a few more years some of these processes will come into operation in actual wastewater treatment plants.

NEW METHODS OF WASTEWATER SLUDGE INCINERATION IN JAPAN

New wastewater sludge incinerating methods aimed at reducing the consumption of supplementary fuel, using fuel other than heavy oil, preventing secondary pollution from exhaust gas and incineration ash, and making effective use of sludge have begun to be practiced. New incinerators, including a single-hearth cyclonic furnace (Maebashi City, 50 Mg/day [55 t/day]) and an FBF with drying hearths (Hygo Prefecture, 45 Mg/day [50 t/day]), are in operation. Of these new wastewater sludge incinerating methods, autogenous combustion is the ultimate technique aimed at cutting the consumption of supplementary fuels. Other new technologies have also been adopted on a full-scale basis, as shown in Table V-7.

Table V-7. *New wastewater sludge technologies used in Japan.*

Process	Merit	Installed Place
Autogenous combustion	a. Elimination of supplementary fuel b. Decrease of pollutants in exhaust gas	a. Takaoka City (MHF, 30 t/day) b. Nagoya City (MHF, 150 t/day)
Cocombustion of sludge and other material		
— with municipal refuse	a. Elimination of supplementary fuel b. Cotreatment of municipal waste	a. Kanazawa City (inclined grate furnace, 150 t/day × 2; ratio of sludge and refuse is 1:6)
— with pulverized coal	a. Decrease of pollutants in exhaust gas b. Decrease in the generation of hexavalent chromium in incinerated ash	a. Yokohama City (FBF, 100 t/day)
Drying by waste wood and autogeneous combustion	a. Effective utilization of waste wood b. Elimination of supplementary fuel for combustion	a. Sapporo City (inclined grate furnace, 150 t/day)
Pyrolysis process	a. Decrease in the exhaust gas volume b. Decrease in the generation of hexavalent chromium in incinerated ash c. Decrease in the amount of supplementary fuel used	a. Sakai City (MHF, 60 t/day) b. Aichi Pref. (MHF, 60 t/day)
Melting of sludge	a. Solidification and stabilization of pollutants such as heavy metals b. Production of aggregate	a. Kawasaki City (electric arc furnace, 16 t/day based on dried sludge with 20 percent water)

Metric ton = 0.907 × tons

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